Alignment of Partnering with Construction IT
Exploration and Synthesis of network strategies to integrate BIM-enabled Supply Chains

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List of abbreviations

ABBREVIATION	EXPANSION
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AEC	Architecture, Engineering, and Construction
AECO	Architecture, Engineering, Construction, and Operations
AIM	Asset Information Model
BIM	Building Information Modelling or Building Information Model
BPM	Building Product Model
BPMN	Business Process Model Notation
BSI	British Standard Institute
CAAD	Computer-Aided Architectural Design
CAD	Computer-Aided Design
CDE	Common Data Environment
CIB	Conseil International du Bâtiment (in English: International Council for Building)
CIC	Construction Intelligence Center
COBie	Construction Operations Building information exchange
COINS	Constructive Objects and the Integration of Systems
CPM	Critical Path Method
CPFR	Collaborative Planning, Forecasting, and Replenishing
CPI	Construction Process Innovation
DB	Design-Build
DBB	Design-Bid-Build
DBM	Design –Build-Maintain
DCM	Design and Construction Management
DD	Definitive Design
EDM	Electronic Document Management
ER	Entity-Relation
ERP	Enterprise Resource Planning
EXPRESS-G	Graphical representation of EXPRESS language
FM	Facility Management
GBA	Government Building Agency
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
HVAC	Heating, Ventilation, Air Conditioning system

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ABBREVIATION	EXPANSION
IAI	International Alliance for Interoperability
IBR	Intensive Big Room
ICT	Information and Communication Technology
IDDS	Integrated Design and Delivery System
IFC	Industry Foundation Classes
IfcOWL	IFC-Web Ontology Language
IMBE	Innovations in Management in the Built Environment
I/O	Input/Output
IPD	Integrated Project Delivery
IS	Information System
IT	Information Technology
L	Large (for scale)
LC	Lean Construction
LOD	Level of Detail
M	Medium (for scale)
M&S	Modelling and Simulation
MBE	Management in the Built Environment
MEP	Mechanical, Electrical, and Plumbing
MF	Multi-Functional (Building)
MNC	Multi-National Corporation
NFC	Near Field Communication
NIST	National Institute of Standards and Technology
OM	Operations Management
ON	Organisational Network
OR	Operations Research
OWL	Web Ontology Language
P/P/A	Process/Product/Actor framework
PAS	Publicly Available Specification
PBS	Product Breakdown Structure
PD	Preliminary Design
PMBOK	Project Management Body of Knowledge
PPP	Public-Private Partnership
PSWS	Project-Specific Web-Site
R&D	Research and Development
RDF	Resource Definition Framework
RFID	Radio-Frequency Identification
RQ	Research Question
S	Small (for scale)
SCM	Supply Chain Management
SCOR	Supply Chain Operations References (model)

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ABBREVIATION	EXPANSION
SME	Small-Medium Enterprise
SN	Social Network
SNA	Social Network Analysis
STEP	Standard for the Exchange of Products
STO	Strategic, Tactical, and Operational
TD	Technical Design
TU Delft	Delft University of Technology
UAV-GC	Uniform Administrative Requirements for Integrated Contracts (In Dutch)
UK	United Kingdom
UoA	Unit of Analysis
USA	United States of America
VDC	Virtual Design and Construction
VMI	Vendor-Managed Inventory
WBS	Work Breakdown Structure

Glossary

This glossary defines the key terms related to the thesis and explains the extent of their interchangeability, where applicable. In the parentheses, the relevant sections and page numbers point to the definitions of these terms inside this thesis.

Actor – In this thesis, an actor is – borrowing the definition of an 'agent' – a coherent group of individuals that behaves intentionally, utilising their knowledge and assumptions for the achievement of a goal. Also, in this thesis, a 'company' is considered an 'actor' (see also below) (see section § 1.3.1, p.9).

AEC, construction industry, construction sector – The Architecture, Engineering, and Construction (AEC) industry is the main area of research of this thesis. It entails the architectural, engineering, and contractor firms that work together towards the realisation of a construction project. The terms construction industry, or construction sector (borrowed from an economics perspective) are used interchangeably with the term 'AEC' (see section § 1.1.1, p.2).

Architect, designer, consultant – The architect is the engineer who designs a construction project. In some countries, the architect is not considered a part of the engineering team and is called designer or design team. In this thesis, the terms 'architect' and 'design team' are used interchangeably. In early literature, the architect is called 'consultant'. In this thesis, a consultant has a consultative function for the architect, e.g. energy consultant, landscape consultant, façade consultant (see section § 1.3.1, p.9).

Building Information Modelling, Building Information Model – Building Information Modelling (BIM) is a set of technologies, tools, and applications for the generation, management, and sharing of Building Information among various AEC actors, based on principles of Information Systems' interoperability. Building Information Modelling is also considered the process of generating this type of information, i.e. the Building Information Model (BIM) (see sections § 1.1.1, p.2 and § 2.4.1, p.41).

Company, organisation, firm – The terms 'company', 'organisation', and 'firm' are used interchangeably in this thesis to signify a legal entity of individuals who delivers an AEC-related service. Other synonyms are 'enterprise', 'institution' or 'corporation', but these are rarely used in this thesis (see section § 1.3.1, p.9).

Construction project, project – A construction project is a sequence of design and execution activities with clear starting and ending points, for the realisation of a

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building or infrastructure. In this thesis, it is generally referred to as 'project' (see section § 1.2.1, p.5).

Contractor, builder – The contractor, in this thesis, is considered the company with the role to carry out the realisation of the construction project. In the literature of the United States of America, it is usually found as 'main contractor' or 'general contractor', to differentiate by any sub-contractors or specialised contractors. In 'lay' language is also referred to as 'builder' (see section § 1.3.1, p.9).

Discipline, domain, specialisation – The various professions in the AEC industry are interchangeably referred to as disciplines or specialisations, e.g. the structural engineer is a different discipline or specialisation with different 'domain' knowledge than a mechanical engineer (see section § 1.1.1, p.2).

Engineers, engineering team – The term 'engineer' refers to the various multi-disciplinary engineers who contribute to the design and engineering of a construction project. In this thesis, occasionally the terms 'engineer' and 'engineering team' are used interchangeably (see section § 1.3.1, p.9).

Framework – In this thesis, the term 'framework' is used in two instances. First, as a 'conceptual framework' of the main parameters of the thesis, as derived from the literature review (Chapter 2), and second, as an 'operational framework', i.e. the suggested model for future action, based on empirical data (Chapter 7) (see section § 7.2.1, p.175).

Function, position – The terms 'function' and 'position' are used interchangeably in this thesis to signify the content of the occupation of an individual inside a company (see section § 1.3.1, p.9).

Integration – The term 'integration' in this thesis is considered the outcome – or end goal – of combining compatible elements to incorporate them. Integration might refer to the integration of social actors, e.g. supply chain integration, or to the integration of similar phases and processes or to the integration of building product information (see section § 2.2.3, p.36).

Model – 'Model' in this thesis is considered the mental abstraction of reality that takes place when one describes a system for the purpose of understanding it. At the same time, in Chapter 7, the term 'model' is used interchangeably with the term 'operational framework' (see also the glossary term 'Framework' above and section § 4.2.2, p.97).

Network – In this thesis, 'network' is the representation of a set of physical things (nodes) and the relations among those things (lines). There are many different types of networks, e.g. social networks or organisational networks (see also below for the defition of a 'Social Network' and sections § 2.7.2, p.59, § 4.2.1, p.95, and § 4.3.1, p.102).

Organisational Network – 'Organisational Network' is considered a network of organisations and their respective relations, e.g. contracts, information exchange, knowledge transfer, etc. (see section § 4.3.2, p.104).

Process – In this thesis, 'process' is considered a series of steps taken to achieve a particular end. This term is used interchangeably with the term 'phase' of a construction project (see section § 1.2.1, p.5).

Product – In this thesis, a 'product' is considered a physical or digital artefact, which might embody or represent a specific function (see section § 2.4.1, p.41).

Role – In this thesis, 'role' is considered the behaviour of an actor, i.e. a firm (see section § 1.3.1, p.9).

SCM – Supply Chain Management (SCM), in this thesis, is a management philosophy that focuses on the management of various tangible, e.g. material or people, and intangible, e.g. information, flows that run among a set of organisations (actors) within and beyond the duration of a project (see sections § 1.2.1, p.5 and § 2.2.2, p.34).

(SC) partnering, alliancing – Partnering and alliancing are, in this thesis, the contractual and other relations among firms for managing various flows among them, i.e. deploy SCM in a specific project (see section § 2.3.1, p.37).

Social Network – In this thesis, 'Social Network' is a network of social actors – or individuals – and their respective social interactions and relationships (see also the glossary term 'Network' above and section § 5.2.2, p.125).

System – In this thesis, a 'system' is a set of (at least two) tangible, e.g. actors or products, or intangible, e.g. principles or procedures, things with interdependent behaviour or properties that work together for the accomplishment of a specific goal (see section § 2.7.2, p.59).

Abstract

Supply Chain Management (SCM) and Building Information Modelling (BIM) are seen as innovations that can manage complexities in construction by focusing on integrating processes and products respectively. Whereas these two innovations have been considered compatible, their practical combination has been mainly anecdotal. The Netherlands was the locale of this study, where both SCM and BIM have been popular approaches. The research objective is to explore their real-world combination and propose strategies for the alignment of SCM and BIM, by viewing Supply Chain (SC) partnering as the inter-organisational proxy of SCM. The main question is: *"How to align the SCM philosophy with BIM technologies to achieve integration in the construction industry? What aspects contribute to this alignment?"*. The methodology was mixed and both qualitative and quantitative data were analysed. The overarching method was case study research and the unit of analysis was the firm, also referred to as 'actor'.

After a semi-chronological review of the relevant literature, the two constructs of SCM and BIM were found interdependent in product-, process-, and actor-related (P/P/A) dimensions. The study consisted of four other consecutive studies. First, empirical insights into the practical implementation of SC partnering and BIM were obtained via the exploration of five cases. Second, a conceptual model for the quantitative analysis of the product-, process-, and actor-related dimensions was designed. Third, this model and mixed methods were applied to two polar (extreme) cases to analyse the contractual (typically SC-related), digital (typically BIM-related), and informal interactions among the involved actors. Fourth, an additional theoretical exploration of the BIM-enabled SC partnerships took place with focusing also on intra-organisational relations within the involved firms. After the four studies, the findings were systematically combined to create the theoretical synthesis, i.e. generate theory. Three consecutive steps of 'construct', 'internal', and 'external' validity took place after the synthesis, to define the transferability of findings. The systematic combination of findings deduced two routes to achieve SC integration in construction: (a) product-related (emphasis on BIM tools), and (b) actor-related (emphasis on SCM philosophy).

The two observed routes to SC integration emerged from the data of the polar cases. Two complementary sets of strategies for SC integration were derived afterwards. These strategies could ease the identification of which route is the 'closest fit' to SC integration, and then support the decision-making of how to pursue it. As the concept of BIM is currently a hot topic, it might be wise to undertake a 'product-related' route to integration and gradually introduce strategies from the 'actor-related' route. However, the 'actor-related' route could attain long-term integration and thus, long-lasting relations among the multi-actor networks. The key aspects of the alignment of partnering with construction IT for BIM-enabled SC partnerships are:

- The identification of whether the SC complexity is of process-, product- or actor-related nature;
- The deployed BIM collaboration patterns, i.e. *ad-hoc*, *linear* or *distributed*;
- The SC coordination mechanisms, e.g. centralised or decentralised;
- The relation between formal and informal aspects, e.g. symmetric or asymmetric;
- The emerging intra-organisational relations due to BIM and SCM implementation;
- The hierarchical level that BIM-enabled SC partnership decision-making pertains.

As the construction industry evolves into an information-driven sector, the alignment of construction IT with inter-organisational management is preeminent for managing the inherent complexities of the industry. In parallel, embracing inter-organisational approaches for information management such as BIM is a promisingway forward for SCM and construction management.

Samenvatting

Supply Chain Management (SCM, ketensamenwerking) en Building Information Modelling (BIM) worden gezien als innovaties waarmee complexiteit in de bouw beheerst kan worden, door het integreren van zowel producten als processen. Hoewel beide innovaties worden geacht verenigbaar te zijn, is de combinatie ervan in de praktijk incidenteel. Dit onderzoek is in Nederland uitgevoerd, omdat zowel SCM als BIM populaire benaderingen zijn in de Nederlandse bouwsector. Het doel van het onderzoek is om te verkennen hoe deze combinatie in de werkelijkheid eruit ziet en om strategieën te ontwikkelen voor de afstemming van SCM en BIM. Hierbij wordt ketenpartnering beschouwd , als de inter-organisatorische component van SCM. De hoofdvraag is: "*Hoe kan de SCM benadering afgestemd worden met BIM technologieën zodat integratie in de bouwsector kan worden bewerkstelligd? Welke aspecten dragen bij aan deze afstemming?*". Er is een gemengde onderzoeksmethode toegepast waarbij zowel kwalitatieve als kwantitatieve data is geanalyseerd. De overkoepelende methode was casus onderzoek en de eenheid van analyse was het bedrijf, in het vervolg ook wel actor genoemd.

Na een chronologisch overzicht van de relevante literatuur zijn SCM en BIM bevonden als wederzijds afhankelijk in de gebieden van product-, proces- en actor-gerelateerde (P/P/A) dimensies. De studie bestond uit vier opeenvolgende studies. Ten eerste zijn er empirische inzichten verkregen in de praktische implementatie van SC-partnering en BIM door een verkennend onderzoek in vijf case studies. Ten tweede is een conceptueel model ontworpen voor de kwantitatieve analyse van de product-, proces- en actor-gerelateerde dimensies. Ten derde is dit model toegepast op twee verschillende cases om te analyseren wat de contractuele (doorgaans SC-gerelateerde) en digitale (doorgaans BIM-gerelateerde) interacties waren tussen de betrokken actoren. Ten vierde heeft er een additionele theoretische verkenning plaatsgevonden van SC partnerships waarbij BIM gebruikt wordt als stimulans voor de samenwerking. Hierbij laagde nadruk op de interne relaties in de organisatie van de betrokken actoren zelf. Na deze vier studies zijn de resultaten op een systematische wijze gecombineerd tot een theoretische synthese. Drie opeenvolgende validatie stappen ('construct' 'interne' en 'externe' validiteit) hebben plaatsgevonden na de synthese om te bepalen in welke mate de resultaten overdraagbaar zijn. De systematische combinatie van de resultaten leidde tot twee routes om SC-integratie in de bouw te bewerkstelligen: (a) product-gerelateerd (nadruk op BIM tools) en (b) actor-gerelateerd (nadruk op SCM benadering).

De twee routes naar SC-integratie kwamen voort uit de tegengestelde casussen en twee complementaire sets van strategieën voor SC-integratie werden nadien hieruit afgeleid. De strategieën kunnen ondersteunen bij de keuze welke route het beste past bij SC-integratie in een specifieke situatie, en vervolgens de besluitvorming over hoe deze integratie na te streven. Omdat BIM momenteel een hot topic is, zou het verstandig zijn om een product-gerelateerde route tot integratie te volgen en geleidelijk strategieën van de actor-gerelateerde route te introduceren. De actor-gerelateerde route kan echter tot integratie op de lange termijn leiden en daarmee tot langdurige, stabiele relaties in de multi-actor netwerken. De sleutelaspecten in de afstemming van partnering voor SC partnerships met BIM zijn:

- De identificatie van de complexiteit in de keten: is die proces-, product- of actor-gerelateerd;
- De gebruikte samenwerkingsvormen in BIM: ad-hoc, lineair of gedistribueerd;
- De SC coördinatiemechanismen, bijv. gecentraliseerd of gedecentraliseerd;
- De relatie tussen formele en informele aspecten, bijv. symmetrisch of asymmetrisch;
- De relaties die binnen een organisatie ontstaan door BIM- en SCM-implementatie;
- Het hiërarchische niveau dat besluitvorming van het ketenpartnerschap met BIM behelst.

Terwijl de bouwsector zich ontwikkelt tot een meer informatie-gedreven sector, is de afstemming van de toepassing van informatie technologie en inter-organisatorische coördinatie bij uitstek geschikt om complexiteit te beheersen. Parallel daaraan is het omarmen van inter-organisatorische benaderingen voor informatiemanagement zoals BIM een veelbelovende stap voorwaarts voor SCM

Synopsis

Οι έννοιες Διαχείριση Εφοδιαστικής Αλυσίδας (Supply Chain Management ή SCM) και Μοντελοποίηση Κτιριακής Πληροφορίας (Building Information Modelling or BIM) αποτελούν καινοτομίες στην βιομηχανία της κατασκευής, οι οποίες στοχευουν στην ενοποίηση των κατασκευαστικών διαδικασιών και προιόντων αντίστοιχα. Παρόλο που αυτές οι καινοτομίες έχουν χαρακτηριστεί ως συμβατές, ο συνδυασμός τους στην πράξη δεν είναι διαδεδομένος. Η μελέτη έλαβε χώρα στην Ολλανδία όπου το SCM και το BIM είναι πολύ δημοφιλείς πρακτικές. Στόχος είναι να εξερευνηθεί η σχέση τους στην πράξη και να προταθούν στρατηγικές για την 'ευθυγράμμισή' τους, θεωρώντας τις εταιρικές συνεργασίες ως αντιπροσωπευτικές της φιλοσοφίας του SCM. Η βασική ερώτηση είναι: «Πώς να ευθυγραμμιστούν η φιλοσοφία του SCM και οι BIM τεχνολογίες για τη μεγαλύτερη ενοποίηση της βιομηχανίας της κατασκευής; Ποιες πτυχές μπορούν να συμβάλουν σε αυτό;». Ακολουθήθηκε μεικτή μεθοδολογία και εξίσου ποιοτικά και ποσοτικά δεδομένα αναλύθηκαν. Η βασική μέθοδος ήταν περιπτωσιολογικές μελέτες κατασκευαστικών έργων και η μονάδα ανάλυσης ήταν η εταιρεία.

Μετά από χρονολογική επισκόπηση της βιβλιογραφίας, τα SCM και BIM βρέθηκαν αλληλοεξαρτώμενα όσο αφορά τα προϊόντα, τις διαδικασίες και τις εταιρίες. Η διατριβή αποτελείται από τέσσερις άλλες διαδοχικές μελέτες. Πρώτον, από εμπειρική ανάλυση πέντε έργων τα SCM και BIM βρέθηκαν αλληλεξαρτώμενα στην πράξη. Δεύτερον, ένα μοντέλο για την ποσοτική ανάλυση των αλληλοεξαρτώμενων προϊόντων, διαδικασιών και εταιριών σχεδιάστηκε. Τρίτον, το μοντέλο αυτό και μεικτές μέθοδοι εφαρμόστηκαν σε δύο ακραίες περιπτωσιολογικές μελέτες για να αναληθούν οι νομικές (από το SCM), ψηφιακές (από το BIM) και ανεπίσημες αλληλεπιδράσεις μεταξύ των εμπλεκόμενων εταιριών. Τέταρτον, μία επιπλέον θεωρητική διερεύνηση των συνεργασιών με BIM πραγματοποιήθηκε με επίκεντρο τις εσωτερικές σχέσεις στις εμπλεκόμενες εταιρίες. Μετά από αυτές τις τέσσερις μελέτες, τα ευρήματα συνδυάστηκαν συστηματικά για να δημιουργήσουν τη θεωρητική σύνθεση, δηλαδή να παράξουν θεωρία. Τρία διαδοχικά βήματα της «μεθοδολογικής», «εσωτερικής» και «εξωτερικής» επικύρωσης έλαβαν χώρα μετά τη σύνθεση, για να προσδιοριστεί το κύρος της έρευνας. Τα συμπεράσματα είναι δύο τρόποι για να επιτευχθεί η ενοποίηση στη βιομηχανία της κατασκευής: (α) σχετικά με προϊόντα (έμφαση στα εργαλεία BIM), και (β) σχετικά με εταιρίες (έμφαση στη SCM φιλοσοφία).

Από τους δύο τρόπους προέκυψαν δύο συμπληρωματικά σύνολα στρατηγικών για ενοποίηση στη βιομηχανία της κατασκευής. Οι στρατηγικές αυτές θα μπορούσαν να στηρίξουν τη διαδικασία λήψης αποφάσεων σε εταιρίες. Δεδομένου ότι το BIM είναι σήμερα πολύ δημοφιλές, θα ήταν ίσως συνετό οι εταιρίες να ξεκινήσουν την ενοποίηση πρώτα υιοθετώντας αυτό. Ωστόσο, η ενοποίηση μέσω SCM δημιουργεί πιο μακροχρόνιες σχέσεις μεταξύ των εταιρικών δικτύων. Οι πτυχές της ευθυγράμμισης των συνεργασίων με το BIM είναι:

- Η κατανόηση του τύπου της πολυπλοκότητας: διαδικαστική, κατασκευαστική ή οργανωτική,
- Ο τρόπος συνεργασίας των εταιρειών μέσω BIM, δηλαδή ad-hoc, γραμμικός ή διανεμημένος,
- Ο μηχανισμός συντονισμού των εταιρειών, π.χ. κεντρικός ή αποκεντρωμένος,
- Η σχέση μεταξύ επίσημων και ανεπίσημων σχέσεων, π.χ. συμμετρική ή ασύμμετρη,
- Οι αναδυόμενες εσωτερικές σχέσεις στις εταιρίες λόγω εφαρμογής BIM και SCM,
- Το ιεραρχικό επίπεδο που η διαδικασία λήψης αποφάσεων για BIM και SCM αφορά.

Καθώς η βιομηχανία της κατασκευής εξελισσόμενη βασίζεται όλο και περισσότερο στον τομέα της πληροφορικής, η ευθυγράμμιση των ροών πληροφορίας με τη φιλοσοφία των εταιρικών συνεργασιών είναι απαραίτητη για τη διαχείριση των εγγενών πολυπλοκοτήτων του κατασκευαστικού κλάδου. Παράλληλα, η συνέργεια μεταξύ οργανωτικών προσεγγίσεων για τη διαχείριση της πληροφορίας, για παράδειγμα το BIM, είναι ένας πολλά υποσχόμενος δρόμος για το SCM και τη διοίκηση στην βιομηχανία της κατασκευής.

Executive summary

Introduction

The Architecture Engineering and Construction (AEC) industry has lately been adopting various integrated methodologies, theories, and practices to control its intrinsic complexities and become more effective and efficient. This doctoral thesis focuses on the *Alignment of Partnering with Construction Information Technology (IT)* as their interaction could render integration in AEC highly possible. The construction sector globally is characterised by complexities, both organisational as well as technical. This study has focused on the construction industry in the Netherlands, to provide insights into the simultaneous implementation of Supply Chain (SC) partnering and Building Information Modelling (BIM). The Netherlands is an ideal setting for this study, given its inherent inclination for collaborative culture and integrative approaches. Besides, the Netherlands has been particularly keen to adopt both Supply Chain Management (SCM) and BIM, in the past. The main objective of the study is to define the impact of the combination of SCM and BIM, aiming at proposing a conceptual and operational framework to achieve integration in the AEC industry. The main Research Question (RQ) was:

"How to align the SCM philosophy with BIM technologies to achieve integration in the construction industry? What aspects contribute to this alignment?"

Subsequently, this overarching question was further divided into the six sub-questions and respective objectives. The objectives and their findings are presented consecutively in the ensuing sections:

Challenges in Design and Construction that SCM and BIM could manage

After introducing the research topic, limitations, and objectives, a literature review was essential for the proposal of a common framework for understanding and combining the two main concepts: SC philosophy and BIM (Chapter 2). Supply Chain Management is an old concept, which emerged in the 1950s from a mere positivistic thinking pertinent to Operations Management. SCM and Supply Chain thinking were transferred to the AEC industry after they had already delivered significant improvements in other sectors, e.g. manufacturing. However, the practical improvements and consequences of applying the SCM concept – or management philosophy – in construction have been debatable for many years. SCM has usually been accused of being a rather ill-defined concept, which delivers neither clear nor consistent benefits to the AEC firms, and hinders competition. Nevertheless, the structured relations among firms, in the form of SC partnerships, could increase the collaboration and induce benefits in the coordination of the information flows among the various multi-disciplinary actors involved in Design and Construction.

To this end, object-oriented modelling – and particularly BIM – is the suggested potential technology to regulate these information flows. The concept of BIM was previously known as Building Product Models and encompassed initiatives, which started around the 1980s, to represent building information in a structured manner. The origins of BIM could be traced back to the long-lasting efforts to standardise the building information through product modelling, from a 'bottom-up' approach, e.g. software companies, industry consortia, and construction researchers. Simultaneously, many efforts to standardise BIM have been made from a 'top-down' approach to regulating BIM in the form of National mandates. As expected, the mismatch between bottom-up and top-down approaches lacks the coordination to popularise BIM effectively. Focusing on structured multi-disciplinary settings and inter-organisational relations, similar to the relations within SC partnerships could prove fruitful towards that direction. This work has adopted an analytical inter-organisational standpoint, to study the simultaneous implementation of SCM and BIM, and to investigate further their potential for managing the Processual, Product-, and Actor-related (P/P/A) complexities of construction.

Real-world interdependences between BIM and SCM concepts

Upon unveiling the conceptual foundations of Supply Chain Management and Building Information Modelling, as these have been layed in the existing scientific literature (Chapter 2), the combination of the two fields was studied in an empirical context (Chapter 3). The analysis included five real-world case studies from the Netherlands, where SCM and BIM were simultaneously adopted. The case study was developed from an explorative and interpretative standpoint. The goal of this empirical exploration was to understand if and how these two concepts – SCM and BIM– are further compatible in practice and whether there are any interdependences or conflicts between them. Due to the afore-mentioned ill-defined SCM grounds, the SC contracts were considered a prerequisite of SCM throughout this thesis. The Unit of Analysis (UoA) is the AEC firm or organisation.

The case studies focus on the real-world applications of SCM and BIM, first as isolated concepts and then as one combined approach. Three main routines of BIM-enabled SC partnering were identified throughout the case analysis: *ad hoc*, *linear*, and *distributed*. The BIM-enabled SC partnerships – and probably other inter-organisational settings – displayed three main BIM-based collaboration patterns, namely:

- *ad-hoc*: on-demand meetings, and exchange of 2D drawings and proprietary files;

- *linear*: selection of BIM-savvy partners, on-demand meetings and co-locations, both firm-based and joint BIM protocols, exchange of 2D drawings and both proprietary and open files;
- *distributed*: BIM-related contract requirements, selecting BIM-savvy partners, pre-scheduled meetings, co-locations, joint BIM protocols, and exchange of proprietary and open files.

The parameters of these patterns are of processual, product-related, and organisational nature, following the P/P/A framework developed in Chapter 2. The concepts of BIM and SCM were found highly interdependent as to the (a) organisational parameter, e.g. combination of contractual means and partner selection criteria, (b) processual parameter, e.g. deployment of physical interactions, such as pull-planning sessions and BIM-related co-locations, and (c) product-related parameter, e.g. use of SC framework agreements, quasi-contractual BIM specification protocols, model checking tools, and standardised information exchange formats. At the same time, roles of key actors in these SC partnerships, e.g. architect, contractor, and suppliers, appeared more enhanced than others. Overall, the two concepts of BIM and SCM were well-compatible, and the individual BIM or SCM practices gradually merged in practice.

Conceptual merging of SCM and BIM to analyse BIM-enabled SC partnerships

Following up on the previous empirical explorations (Chapter 3) around the collaboration of BIM-enabled SC partnerships, the conclusion was that additional analytical methods would be useful to capture the interdependences fully at a process-, product-, and actor-related dimensions (P/P/A) of BIM-enabled SC partnerships (Chapter 4). The previous findings of the transforming roles of the SC partners – or actors – suggested the need for a detailed analysis of the SC coordination process. The intention was to materialise the interdependences between SCM and BIM in a modelling framework applicable to the analysis of various BIM-enabled SC partnerships. Modelling was selected as a compatible approach with both domains, i.e. SCM and BIM. After analysing various modelling approaches in construction, input from Organisational Networks, process-, and product modelling were used. As the model is developed in an Entity-Relation fashion and from a network perspective, it is extendable and close to reality respectively.

The SC coordination mechanisms were explored through the development of a SC analysis tool, based on the combination of product models with processual and organisational information in a structured graph-based model. Besides illustrating the processual, product-related, and organisational complexities of AEC, the developed model was applied as a proof-of-concept to a real-world case study. The findings from the case identified an imbalance in the relation between the project phasing and the interactions of key actors, either internal to the SC partnership, i.e. strategic, or external. The findings of the scenario case suggest that the analysis of the coordination in BIM-enabled SC partnerships requires not only the analysis of the information flows but also the analysis of the processes and inter-organisational networks. Analysing those will allow for drawing inferences upon ways to improve the BIM-enabled partnerships.

Relation between formal and informal aspects of BIM-enabled SC partnerships

After these conceptual explorations, further deep pragmatic analysis was conducted using the developed BIM-based SC analysis tool (Chapter 4) to explore not only the inter-organisational relations from BIM-enabled SC partnering but also the various formal, e.g. contractual, and informal relations among the SC actors (Chapter 5). Instead of focusing on all five cases from the previous pool of projects, the analysis tool for BIM-enabled SC partnerships was applied to a set of polar (extreme) cases, recruited from the cases that participated in the empirical exploration study (Chapter 3). The selection of the two cases was due to their advanced levels of the BIM-based collaboration process, i.e. *distributed* pattern, and their antithetical SC composition and strategies; one being 'demand-led', because the client participated in the long-term contract, and the other 'supply-led', as the architect was also included in the partnership.

Following a mixed methods approach, the previously developed analysis tool was complemented with qualitative case research to analyse the contractual (formal), digital, and informal relations, in BIM-enabled SC partnerships. The inter-organisational relations were found disproportionally asymmetrical between the two cases. In the first case, whereas the contractual relations were numerous, the informal communications were minimal and rarely surpassed the contractual prescriptions of the SC. In the second case, whereas the contracts were long-term, the SC actors relied less on the contractual aspects and more on their informal communications across multiple tiers. In essence, the first partnership was transactional, whereas the second, relational. Thus, the integration of the BIM-enabled SC partnerships also depends on the shared partnering goals of the SC partnership, and on the composition of the strategic or internal partnership. Overall, the *distributed* BIM collaboration pattern of Chapter 3 requires additional informal aspects of communication to diffuse BIM knowledge and experience across the SC partnership and further promote SC integration throughout the design and construction phases.

Emerging intra- and inter-organisational relations in BIM-enabled SC partnerships

Having looked into the formal and informal inter-organisational relations during the pragmatic explorations (Chapter 5) of BIM-enabled SC partnering, it became evident that an additional research for the study of intra-organisational relations was required (Chapter 6). Throughout the pragmatic explorations (Chapter 5), unexpected insights into the intra-organisational relations of the participating firms proliferated. The intra-organisational level of the BIM-enabled SC partnership was not previously considered in the thesis, as the UoA was the firm. Chapter 6 revisits the analysis of the two polar cases of the previous chapter, this time as to their intra- and inter-organisational relations. The cases were analysed based on a past key conceptual framework of SCM implementation, used as a theoretical lens for the analysis of the case narratives. The analysis highlights two paradoxes. First, the *SC Planning* is considered either the outcome of *Joint SC Operations* (case A) or of shared SC *Scope* (case B) in the polar cases, and thus, it relates to different hierarchical levels per case. A second paradox is the consideration of *Communications* as the result of either pre-existing *Trust* (case A), or of intensive project-based *Joint Operations* (case B). Therefore, the concepts of BIM and SCM and their deployment from SC partnerships depend on the pre-existing history and cultural alignment –at an operational level – primarily, rather than the contractual agreements – at a strategic level. To further strengthen the BIM-enabled SC partnerships, explicit shared SC scope, and BIM-related agreements are preeminent.

Whereas the initial research focus was the AEC organisation, additional intra-organisational insights into the firms of engineers, contractors, and suppliers were obtained, and particularly as to the alignment of their business models with BIM-enabled SC partnerships. Several aspects at the periphery of the research objectives are essential for instigating further integration of the BIM-enabled SC partnerships:

- Motives for BIM & SCM adoption: whether it is external or internal for each involved SC firm;
- Synergy among intra-firm hierarchy: whether the firms are of rigid or horizontal hierarchy;
- BIM & SCM vision into firms' business plan: whether it is opportunistic or incorporated;
- Intra-firm BIM-related functions: whether there are multiple or all-around BIM functions;
- Services offered per firm: whether the firms offer specialised or integrated services;
- BIM implementation by the firm: whether the BIM is out-sourced or generated in house.

The above intra-organisational aspects pertain to various hierarchical levels, from top management to work floor. Surprisingly, these intra-organisational aspects were found on various types of AEC firms and were not discipline-dependent. From the above observations, not only SCM philosophy, but also the concept of BIM deeply affects both the inter- and intra-organisational structures of the AEC firms. Further aligning the intra-organisational business models to the scope and vision of the BIM-enabled SC partnerships is essential for inducing SC integration.

Integrated BIM-enabled SC partnerships after the alignment of SCM with BIM

After the empirical insights (Chapter 3), conceptual experimentations (Chapter 4), pragmatic explorations (Chapter 5), and theoretical re-visiting (Chapter 6) of the emergent phenomenon of BIM-enabled SC partnering, the findings from each chapter were combined in a systematic and reflective manner to create the theoretical synthesis, i.e. generate theory. In parallel, three consecutive validation steps of 'construct', 'internal', and 'external' validity took place after the theory generation, so as to delimit the boundaries and applicability of the research and increase its value. The systematic combination of the research findings was used to deduce two sets of strategies for BIM-enabled SC partnerships, pertaining to two different routes to achieve integration in AEC: (a) product-related, i.e. emphasis on BIM tools, and (b) actor-related, i.e. emphasis on SCM philosophy.

The two *polar* (extreme) cases of BIM-enabled SC partnerships formed the basis for the suggestions to reshape and integrate other similar constellations. The two cases followed a 'product-related' route and an 'actor-related' route to integration respectively. From the combination of the observed activities to achieve integration throughout the cases, and their respective gap analysis, a set of network strategies for SC integration is extracted. These two sets of strategies and the respective outcome of the validation sessions are presented in Table 1 and Table 2. The strategies do not differentiate as to processual, product-related, and organisational dimensions of the P/P/A framework, which was developed in Chapter 2, so as not to further hinder integration. Given that the strategies pertain to various intra-organisational aspects, they are categorised into the three hierarchical levels, i.e. strategic, tactical, and operational, to facilitate their adoption from firms that participate in SC partnerships or other structured multi-actor networks. Accordingly, depending on the hierarchical level that the strategies are categorised, they pertain to various functions from top management to middle management and project engineers.

TABLE 1 Strategies for SC integration via the 'actor-related' route, including the results of the validation.

LEVEL	'ACTOR-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUTCOME
Strategic	1. Issuing explicit formal SC framework agreements with elements of BIM protocols;	Yes*
	2. Partnering with firms with integrated business models, e.g. MEP firms;	Con*: large projects
	3. Top management support for SCM adoption and inter-organisational synergy;	Con: engagement
	4. Adjustment of BIM scope and planning to the SC's scope and commercial decisions.	Con: project manager
Tactical	5. Establishment of permanent contact persons across the SC partnership;	Inc*
	6. Early involvement of the suppliers in the Design and Engineering phases;	Con: trust
	7. Pre-scheduling frequent and time-wisely strategical co-locations for BIM collaboration;	Yes
Operational	8. Sharing a collective future vision for both BIM and SCM at a work floor level;	Con: clear BIM scope
	9. Encouragement of informal communication across multiple tiers;	Yes
	10. Balance between internal and external SC actors and reciprocal interactions;	Con: co-locations
	11. SC partnership's flexibility and adaptability to obscure phase boundaries;	Inc
	12. Increase of intra- and inter-firm communications to increase commitment trust;	Yes
	13. Digital information exchange of IFCs and proactive informal ad-hoc communications.	Con: trust

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

TABLE 2 Strategies for SC integration via the 'product-related' route, including the results of the validation.

LEVEL	'PRODUCT-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUT-COME
Strategic	1. Selection of BIM-savvy partners and in-house BIM investment, instead of outsourcing;	Inc*
	2. Alignment of the firms' BIM readiness with the SC partnership's BIM maturity level;	Yes*
	3. Partnering across firms with compatible BIM (internal/external drive) and SCM visions;	Inc
	4. Joint SC agreements about the BIM protocols and clear project/SC BIM scope;	Con*: BIM manager
	5. Alignment of the BIM models with local BIM specifications and National BIM policies.	Yes
Tactical	6. Joint agreements on the BIM LODs and clear design accountability;	Con: trust
	7. Clear role of BIM coordinator and choice between the proprietary or open deliverables;	Yes
	8. Inter-firm BIM peer-learning and training;	Con: clear BIM scope
	9. Elimination of the gap between strategic and operational planning at SC and firm levels.	Con: project manager
Operational	10. Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns;	Yes
	11. Information exchange of IFCs and provision of stable physical and digital infrastructure.	Con: clear BIM scope

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

Concluding remarks

As the two observed routes to integration emerged from the cases, it is advisable for construction managers that their respective strategies (Table 1 and Table 2) would not be deployed in isolation, but instead complementarily. The strategies could facilitate the identification of which route is the 'closest fit' to SC integration, and then support the decision-making about how to pursue it. Given that the concept of BIM is currently a hot topic, it might be wise to undertake a 'product-related' route to integration and gradually introduce strategies from the 'actor-related' route. However, the 'actor-related' route could attain long-term benefits for SC integration and thus, long-lasting relations among the multi-actor construction networks. The long-term trusting relations among the various actors could, in turn, prepare the ground for innovation change management and smoother adoption of future construction IT developments. The key aspects of the alignment of partnering with construction IT for long-standing, young, or future BIM-enabled SC partnerships are:

- The type of the complexity in the BIM-enabled SC partnership, e.g. whether it is of processual, product-related, or organisational nature (Chapter 2);
- The deployed BIM collaboration patterns, i.e. *ad-hoc*, *linear* or *distributed* (Chapter 3);
- The SC coordination mechanisms, e.g. centralised or decentralised (Chapter 4);
- The relation between formal and informal aspects, e.g. symmetric or asymmetric (Chapter 5);
- The emerging inter- organisational and intra-organisational relations (Chapter 6);
- The various inter- organisational and intra-organisational hierarchical levels of decision-making that BIM-enabled SC partnership pertains (Chapter 7).

From the above, it is concluded that the alignment of partnering with construction IT is a complex task for innovation change management that requires the introduction of additional organisational and other, completely new, information-based considerations to the toolbox of construction managers and researchers.

1 Introduction

Chapter summary

The thesis on the 'Alignment of Partnering with Construction Information Technology (IT): Exploration and Synthesis of network strategies to integrate BIM-enabled Supply Chains' offers an understanding of the Building Information Modelling (BIM) and Supply Chain Management (SCM) concepts and their combination through the lenses of collaboration, coordination, and integration. This first chapter includes insights into the status of the Architecture Engineering and Construction (AEC) industry globally and in particular in the characteristics of construction in the Netherlands, where the research took place. It describes the research area, contains a short definition of the main terminology and explains the motivation for the study. Thereafter, this chapter introduces basic concepts, issues, and theories that will be further critically reviewed in the background chapter (Chapter 2). Next, it underpins the research problem and proposes a potential solution to it.

Having analysed the relevant research gaps omitted from the existing recent research on BIM and Supply Chain Management (SCM), this chapter presents the research objectives and questions. Subsequently, after defining the research goals, the chosen research design to achieve them is presented. Both inductive and deductive reasoning was held at times, and simultaneously, both qualitative and quantitative data have been collected and analysed. The potential impact of this doctoral thesis is highlighted as to the (a) regional, (b) societal and (c) scientific relevance and its research limitations. Finally, this chapter outlines the structure of this book by associating the research questions to the corresponding chapters of the thesis, as well as a short guide to the reader.

§ 1.1 Background

§ 1.1.1 Building and Construction industry

The construction industry has had a pivotal role worldwide. The advancements in the construction of building and infrastructure are strongly linked to the maturity and economic power of the global community. It is estimated that in Europe, the Gross Domestic Product (GDP) of the construction industry is 10% (EuropeanCommission, 2015). The construction market is globally highly important economically as also highlighted by the quick translation of the housing bubble in the construction market into a financial crisis in the United States of America (USA). Therefore, the construction industry is a quite volatile market. However, it is suggested by industry reports that after 2020 the construction industry in Western Europe will return to the "pre-crisis levels" (Timetric, 2015). Thus, it will soon resume playing a vital role in the economy.

Apart from its economic importance, the construction industry consists of numerous professionals with various backgrounds and specialisations who perform architecture, engineering or other construction professions, and are organised in heterogeneous firms or coalitions of firms. The construction sector has been considered synonymous with the Architecture Engineering, Construction, and Operations (AECO) industry. In the context of this thesis, the industry has been referred to as Architecture Engineering and Construction (AEC) industry, as the owners' organisations are rarely discussed and occasionally researched. The terms *AEC* and *construction industry* have been hereafter used interchangeably. These multi-disciplinary construction firms are rarely in sync with each other, as their various specialisations are diverse and range from managing real estate portfolios to producing lighting fixtures. So far, the individual firms of AEC have focused on and achieved improved performance in a content-based and intra-organisational manner by applying customised principles of Operations Research (OR), such as scheduling and process management.

In the manufacturing sector that is more homogenous – and possibly more simplistic – than the AEC, the advancements in the field of OR gradually led to the rationalisation of quality, logistics, business organisation, and partnerships. Supply Chain (SC) research surfaced after that period, approximately in the mid-80s (London & Kenley, 2001). Initially, a Supply Chain was represented by a set of flows: a downstream flow of material, an upstream flow of transactions and a bidirectional flow of information (Christopher, 1992). SC Management (SCM) is a philosophy that theorises and suggests activities for the regulation of these flows. Later, a Supply Chain was considered actually to be a network and not a – linear – chain per se, given that the multiple organisations that form this network, generate different and multiple information streams simultaneously (Christopher, 2005). The 'network' view of the concept of SCM is traced back to the beginning of the nineties as both permanent and temporal networks (Davidow & Malone, 1992). As Christopher (2011) has described, a Supply Chain could be considered as a "supply-demand network", or a complex and distributed network of organisations.

The geographically distributed character of manufacturing industry has been facilitated by sophisticated applications of Information Technology (IT). Similar IT support has been applied to several activities of AEC. Until recently, Computer Aided Architectural Design (CAAD) software was the standard tool of computerisation in architecture and its use not only portrayed the contemporary architectural process but also increased the performance of AEC significantly by supporting automated, semi-automatic, and standardised processes (Aouad, 2012). More than a decade ago, the term Building Information Modelling (BIM) was introduced. BIM is a technology-driven approach that includes integrated software solutions for AEC. BIM is an integrative technology with "parametric intelligence" for the AEC (Eastman, Teicholz, Sacks, & Liston, 2008). Since it generates, collects represents and manages building project information, it could potentially support the management of the - information flows of the SC. Although there is a plethora of BIM definitions and interpretations, for this thesis, BIM is considered a promising set of technologies for generating, sharing, and managing building information among various AEC actors. Thus, this thesis adopts a more engineering and managerial, rather than a purely sociological standpoint.

This research is based on the two standpoints of management theory and technological developments. On the one hand, it used SCM as an integrative concept that encompasses the organisational-, process- and product-related aspects of the construction SC. On the other hand, it used BIM as an information-driven technology that could achieve integration of the SC network by structuring and regulating the information flows. The research will navigate equally and concurrently between theoretical and technological stands.

§ 1.1.2 Motivation

Despite the economic importance of AEC, which was mentioned above, the construction industry has an immediate societal impact, given that it not only employees numerous individuals but is also responsible for sheltering the basic human needs and shaping the Built Environment. Therefore, the research on the broad area of AEC is highly relevant to architects. The PhD research topic was advertised as the job position from the Department of Real Estate and Housing – currently named Management in the Built Environment (MBE) – within the Faculty of Architecture at Delft University of Technology (TU Delft). The research problem of this thesis was initially proposed as an extension of the dissertation of Vrijhoef (2011), but with an additional focus on BIM. The description of the job post and scope of this PhD research were initially stated as follows in the advertisement of the doctoral position:

"Various attempts have been endeavoured to move the building industry away from its traditional and fragmented approaches to the organisation and coordination of the supply chain. Supply chain integration has been applied in many various modes in building to improve its performance. Much of the applications have implied intensified and integrated information sharing among industry partners. The approach and software solutions of Building Information Modelling (BIM) have already given various indications of how this can be achieved, particularly in the design stage, and promises to contribute further to supply chain integration. The PhD candidate is expected to analyse the applicability and usability of BIM throughout the supply chain of the build environment and develop a theoretical and operational framework that guides BIM deployment promoting and supporting supply chain integration. The main issues of the research are: (a) Coordination among different organisations in the supply chain and various stages of the life cycle, (b) Integration of information, decision-making and logistics, (c) Continuity of information on products and processes, (d) Costs and benefits of BIM in the supply chain".

After a successful application process, the author – heretofore called researcher – was hired to conduct this PhD research within four years, starting in November 2012. The position was financially supported during the first year from the Knowledge Centre of Construction Process Innovation (CPI), and afterwards from the MBE Department.

As the majority of SC-related research aims to ameliorate the whole industry, this PhD similarly had a broad scope, which was not initiated by a specific firm – 'problem owner' – or triggered by a specific problem. Therefore, this research did not have a specific 'problem owner'. As one of the numerous architects that have been engaged in designing and forming the built environment, the personal experience shaped the researcher's motivation for the study. The classic architecture theory considered the construction process as continuous and not fragmented – as it currently is – but governed by a *masterbuilder* (Vitruvius, 1523). Nowadays, many different specialisations – or disciplines – in the Built Environment perform numerous specialised activities (Winch, 2002). The AEC industry is nowadays well-advanced regarding the three pillars of classical architecture about function, fitness, and form and it is now seeking for progress and innovation in optimising the mechanics and its organisational, processual, and product-related components. The contemporary problems of AEC are closely related to the lack of discipline-specific management approaches, rather than technical or aesthetical considerations. To this end, the researcher did not hold an architectural mindset throughout this research, rather than an unbiased – generic – managerial standpoint instead, aiming at understanding the intersection of BIM and SCM from the perspectives of various actors, across multiple tiers, with the aim to foster greater synergy among them.

§ 1.2 Problem statement

§ 1.2.1 Research problem

Despite being an important industry, AEC traditionally experiences many losses during its performance, such as time delays, cost overruns, and consequently low building quality. These losses are either on material or on time and, thus, costs. For example, in the United Kingdom (UK), around a 32% of the landfill waste is due to the activities and materials in the construction industry (DEFRA, 2006). Also, from the construction materials that arrive on site, around 13% are never used, instead are being consigned to landfill (DEFRA, 2007). Likewise, more than 30% of the building projects cannot reach the schedule or budget plans (CMAA, 2007). These losses take place due to the fragmentation of the industry into smaller parts, which entails a lack of sharing accurate and updated information among the various professionals. In the Netherlands, for example, the construction firms were traditionally considered primarily price-driven in the past (Rijt, Hompes, & Santema, 2010). This image suggests an AEC SC that is loosely interrelated, unreliable, and inefficient. It was only recently that considerations such as quality management, integration, and performance evaluations came into the foreground of AEC research. At the same time, a growth of 70% is expected until 2025 in the building industry, which necessitates new directions in research and practice to improve the existing image (HMG, 2013).

Although these symptoms of low performance are process-based and could relate to the operations of construction, they are largely generated from organisational malfunctions and the usually unique and not repetitive character of the construction projects. A construction project is – like any other project – a sequence of inter-connected activities for the accomplishment of a specific goal within a particular time frame (Wysocki, 2011). Most construction projects are unique and involve numerous construction companies. O'Brien et al. (2009) stated that the AEC industry has a "highly fragmented" structure. The fragmentation of AEC is located not only at the processes, as stated before, but also to the organisations that form it. This fragmentation could also be described as 'disintegration', i.e. the "incongruent goals and consequent divergent behaviours" of various involved firms, according to Nam and Tatum (1992). Due to the lack of collaboration and coordination between the various organisations that participate in a project, the industry underperforms. This barrier is located in all the relative phases – essentially the temporally confined processes for delivering a particular fragment of a project – of the industry: initiation, design, construction, and operation. At the same time, all key actors are to varying extents involved in various phases of the AEC lifecycle. This research views the need to integrate the AEC SC as a collective challenge for all actors.

The AEC industry is nowadays more complex than ever. This complicated reality originates from the high number of participants in the project chain, the fragmentation of the delivery processes, as well as the technical challenges present in the project brief (Winch, 2002). SCM practices are applied in various construction operations to achieve collaboration among its members and counterbalance some of the uncertainties above, e.g. regulating the cash and material flows, as well as ensuring a trusting environment among the various SC participants. Likewise, BIM – being an integrative technology for the AEC – is a structured approach to counterbalance some of the complexities currently present in AEC, e.g. managing the technical complexities of the construction projects and caring for improved communication and collaboration.

Apart from the advancements from individually applying SCM philosophy and BIM technology in construction projects, even greater improvements could be achieved by their combination, given that they have been previously conceptually linked (Nederveen, Beheshti, & Ridder, 2010; Nummelin, Sulankivi, Kiviniemi, & Koppinen, 2011; Vrijhoef, 2011). However, the fusion of these two fields has not yet been researched, and potentially new challenges might surface from their combination. First, although BIM promises a quite 'centralised' collaboration, it is rarely fulfilled – at least in a synchronous manner (Cerovsek, 2011) – due to interoperability issues and "lack of software compatibility" (Berlo, Beetz, Bos, Hendriks, & Tongeren, 2012; Chien, Wu, & Huang, 2014). Therefore, although BIM is promising for managing the SC information flows, is not yet fine-tuned to support them fully. Second, despite the advancements in time and cost management offered by BIM, as a technology change, it induces an external project risk that requires special attention, in organisational and legal issues (Tah & Carr, 2001). The managerial shift that accompanies BIM causes "workflow transition difficulties" (Chien et al., 2014). Third, BIM has not been yet extremely fruitful into managing the information flows among the various disciplines that use it and among any potential SC partners. Thus, there are remaining technical, operational, and organisational challenges despite the application of integrative theories and technologies in AEC.

§ 1.2.2 Potential solution

The problems of the construction industry pertinent to process-, product- and organisation-related issues are not to be treated in isolation. Since the AEC SC resembles a network of distributed control, it suggests a complex system. Every system accounts for more than the sum of its parts (Aristotle). Therefore, the AEC SC cannot be broken down into its components and improved individually. Thus, a comprehensive approach was undertaken in this research. However, a distinction should be made between deterministic and non-deterministic systems. In this thesis, although the AEC industry is viewed as a loosely-coupled system (Dubois & Gadde, 2002a), composed of tangible and intangible components, it is not fully deterministic, but its components – and in particular the information flows and interactions – are highly inter-dependent instead. A potential solution to the afore-described problems that would support more manageable and consistent information flows could subsequently reduce the waste, optimise the processes, improve the efficiency in cost and time projections, and integrate the SC of firms to even more engaging and long-lasting inter-organisational relations. It will then also improve the quality of the building product and therefore of the building environment.

An opportunity has been presented to the construction industry for optimisation and inclusiveness from applying the SCM philosophy and BIM-based tools. Both SCM and BIM are quite integrative in nature. The former is an integrative management philosophy that takes into consideration the whole SC as a network of organisations that interacts with a long-term perspective. The latter is an integrative technology that ensures an uninterrupted and easily maintained structure of building information throughout the building life cycle. These two solutions alone have already transformed construction with providing structured relations and advanced technical infrastructures respectively. For example, 70% of the contractor organisations report a positive ROI on BIM investment (McGraw-Hill, 2014). At the same time, the contractors had expected that their BIM-related projects will increase by 50% within two years (McGraw-Hill, 2014). Apart from its increased adoption worldwide, viewing BIM as a systemic innovation, which affects numerous players in the market, it would be potentially relevant to combine it with SC integration and SCM in construction, as systemic innovations by nature are inter-organisational (Lindgren, 2016). *This research argues that from combining the two, SCM and BIM would be mutually improved. SCM could be equipped with a BIM-based information flow. The reverse also holds true; since BIM technology could be favoured from an already structured and trusting environment where SCM is applied, and inter-organisational issues quite regulated.*

The challenge of this research is not only to examine whether SCM philosophy and BIM technology are compatible in practice, or trace the real-world aspects of their combination but also to propose a set of strategies to evaluate and improve the impact of this socio-technical mix. Currently, SCM is quite widespread in construction, approximately three decades since its introduction as a management philosophy. In some countries, SCM is more popular than others. However, the diffusion of SCM philosophy is relatively slow in comparison to the diffusion of BIM technology, which has been considerably intense the last decade. Most architectural firms use BIM (Froise & Shakantu, 2014), but with different levels of sophistication. From the contractors' viewpoint, the BIM-enabled projects are about 50% of their business (McGraw-Hill, 2014). This research projects to the future of AEC where such integrated theories and technologies could be simultaneously applied.

§ 1.2.3 Research gap

Currently, SCM and BIM are linked only conceptually and not substantially. BIM practices in AEC overlook several organisational parameters of integration, although there are reports on the changing dynamics of the roles of the participants induced by BIM (Sebastian, 2011b). Presently, existing research on BIM includes reports and projects on virtual team collaboration (Becerik-Gerber, Ku, & Jazizadeh, 2012), team integration through BIM and Integrated Project Delivery (IPD) (London & Singh, 2013), or collaborating BIM networks (Grilo, Zutshi, Jardim-Goncalves, & Steiger-Garcao, 2013). But in all these approaches, there is no emphasis on strategic SC relations, i.e. relations of long-term partnerships. Often, BIM research focuses on a small sub-group of the project team. BIM is used in an ad-hoc manner, partially, and incompletely. On the contrary, SCM research, in general, focuses on a larger group of stakeholders. Moreover, the involvement of specialised consultants transforms the team dynamics in an AEC project, by changing the levels of trust among the organisations. Therefore, the gaps in this research area are situated in both organisational and technical aspects.

Given that SCM philosophy is a largely ill-defined concept (Chen & Paulraj, London & Kenley, 2001; 2004), the concept of 'partnership' was included in the study. The SC partnerships are constellations of firms, usually consisted of 'dyadic' partnering relations from the contractors towards multiple tiers, which attempt to manage the SC by adopting practices that focus, among others, on enhanced collaboration (Lambert, Cooper, & Pagh, 1998). To this end, BIM could be considered a relatively permanent – and possibly long-term and strategic – digital set of technologies for SC partnerships. This partnership would not be disbanded and re-invented in each project, as the virtual corporation described by Davidow and Malone (1992) does, but instead, the involved partners would carry experience, knowledge, and communication channels from one project to another, without necessarily constructing a repetitive project. Also, this research focused not only on the collective behaviour of the partnership but also on the individual characteristcs of the involved partners. After all, governmental reports, such as of Sir Egan's Report (1998) in the UK, have been envisaging such a new type of collaboration of the supply chain through partnering. However, supply chain collaboration is more meaningful when intentional, strategic or long-term. Therefore, the concept of SCM has been reviewed only within the inter-organisational boundaries of contractual SC partnerships that apply BIM technologies as a part of their long-term collaboration, and not as simply an orientation (Mentzer et al., 2001).

Again, these socio-technical gaps regarding BIM implementation are located not only in the operations and the intra-organisational level but also at an inter-organisation level, which could be related to SCM adoption. Surprisingly, in both academic and market environments, the reported benefits, limitations and impact of BIM are restricted to single-firm perspective, e.g. the contractors in the McGraw Hill's report (McGraw-Hill, 2014). Given that BIM provides the means for coherent, and continuous information flows among the various AEC firms, it is necessary to evaluate the business value of BIM also at an inter-organisation level. *Thus, there is a gap in the socio-technical impact of BIM-enabled SC partnerships, which could both support the long-term scope of the SC partnerships and leverage from BIM technology, and particularly as to the collaboration processes, tools, and the explicit and implicit functions and roles of the involved firms and individuals.*

§ 1.3 Research objectives and questions

§ 1.3.1 Aim

Previous research on the interface of BIM and SC thinking has focused on assessing the inter-organisational implications of the use of ICT in construction projects (Adriaanse, 2007). This thesis focuses on solely the use of BIM technology as a construction IT and aims to discuss the transformations of the AEC SC partnerships through BIM and vice versa: change the BIM collaboration process by applying SCM thinking. Thus, it does not only hold an inter-organisational view but also hold a long-term perspective, which is envisaged from SC partnering. The research focuses on an inter-organisational level across firms from multiple construction tiers, by considering the organisation – also referred to as 'actor' – as a Unit of Analysis (UoA). An organisation is considered a "purposeful system" that contains at least two purposeful individuals who have a common purpose (Ackoff, 1971), and behaves like a rational agent (Giddens, 1984) with a consistent role. Therefore, the 'system' in this thesis stands for the SC (partnership) and the 'actor' stands for the various multi-disciplinary AEC firms.

Accordingly, various construction firms might participate in these SC partnerships, e.g. architects (traditionally considered as the clients' personal problem-solvers), engineers (essentially the designers of the structures and building services), contractors (the key actor for construction coordination), and suppliers (Winch, 2002). To increase the pragmatic relevance of the study, the intra-organisational levels of top firm management, project managers, and BIM employees (draughtsmen, engineers or coordinators) were also analysed, referred to and as 'functions' (Ackoff, 1971). Therefore, the inter-organisational collaboration in BIM-enabled SC partnerships is analysed as to the collaboration processes, tools, and the explicit and implicit functions and roles within the involved firms and individuals.

Improved collaboration among the design team, the contractors, and the client organisations has been already reported for BIM from various scientific and market reports (Azhar, 2011; Bryde, Broquetas, & Volm, 2013; McGraw-Hill, 2014). This research also investigates their motives, willingness, and capacity to establish – or retain – transparent, trusting, and reciprocal relations and to engage in long-term collaboration. Subsequently, apart from sharing risks and rewards, they would induce greater market stability from their engagement to using BIM. While larger teams seem to benefit the most from engaging with BIM (McGraw-Hill, 2014), this research intends to promote SCM as a solution for the challenges in BIM processes in multiple types of firms. It is assumed that subsequently all the organisational structures, roles, and processes of AEC will be transformed by the introduction of BIM as an integrated technology for supporting the SC information flows.

BIM as an IT includes a variety of tools, practices, and norms. Although there is currently an abundance of BIM rhetoric, it has not achieved the appropriate socio-technical maturity to become an indisputable standard for the industry. From the flows that have been traditionally considered parts of a Supply Chain – material and information (Christopher, 1992) – this research focuses only on the information flows among the SC actors that define the collaboration, following the managerial standpoint of Winch (2002). After all, the information flows are primarily responsible for distributing the material, and cash flows and the information and the interactions among the project actors are crucial for the remaining flows. The SC information flows are enriched by the computational infrastructures of BIM and the consistency of project building information.

The research aims to clarify and redefine the interfaces between SCM and in particular SC partnership, and BIM. BIM is then suggested as an integrator of the SC information flows. The underlying hypothesis of the thesis was that the coherency of the information flows from BIM applications could increase the transparency and consequently the trust among the SC partnership. BIM-enabled SC partnerships encourage the involved SC actors to share their responsibilities and, therefore, common risks and rewards. This research does not intend to accept BIM uncritically as a panacea for all the challenges that AEC faces, but to apply SCM concept and practices to BIM adoption. The objective is to get BIM "*supply chain-ed*" and not the AEC SC partnerships simply "*BIM-ed*".

*Thus, the main research objective is to describe the repercussions of the intersection between the SCM and BIM concepts not only regarding efficiency and effectiveness – for the products and processes – but also on the structure of the inter-organisational network of the AEC SC partnership*s. Subsequently, the study seeks to improve and align SCM with BIM by providing practical solutions. The word 'repercussions' was selected to denote the exploration of the combination of BIM and SCM philosophy, given that 'repercussions' carries a neutral, indirect, or unforeseen connotation, and implies a reciprocal action from the two constructs in question, i.e. SCM and BIM. The word 'intersection' is embedded in the main research objective of the thesis, borrowed by the Set Theory in Mathematics, to explain the relation between the two main constructs, i.e. SCM and BIM. Figure 1 illustrates different operations between two notions, e.g. SCM and BIM. Given that the two main constructs under study are quite incomparable, as SCM pertains to a management philosophy (Vrijhoef, 2011), and BIM to a "set of instrumentalities" (Miettinen & Paavola, 2014) the two are not fully combined in this research. Therefore, only the intersection of the two, i.e. the aspects that apply to both SCM and BIM, is studied in this research (see Figure 1). These aspects are discussed further in the Chapter 2, and would be eventually defined further in Chapter 8.

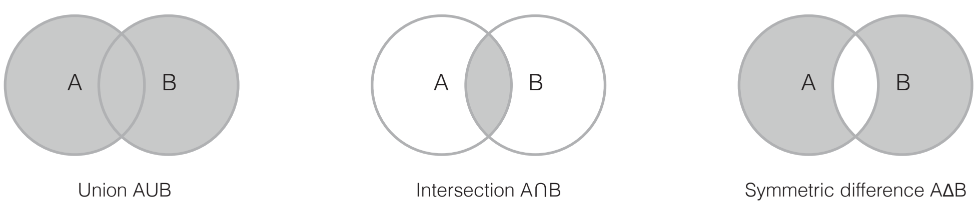

FIGURE 1 Various types of relations between the constructs of BIM and SCM, and the selected relation (intersection).

§ 1.3.2 Research questions

The main question describes the central research aim in an overarching manner. The main question was further analysed in "what" and "how" -type sub-questions.

– **How to align the SCM philosophy with BIM technologies to achieve integration in the construction industry? What aspects contribute to this alignment?**

The terms 'align' and 'alignment' are used in the main Research Question (RQ), following their abundant appearances in SCM literature, such as of Mentzer et al. (2001), and Lambert et al. (1998), where 'alignment' refers to the evaluation of the extent to which various managerial and behavioural components of the firms concur. The dissertation has three main parts: a *description* part, which contains the background to create the domain knowledge of this research, an *analysis* part, which contains the main research explorations, and a *synthesis* part, which combines the related domains into the main research products, theoretical synthesis and model or operational framework. The *description* part contains the background questions of this research, which in turn are answered through the literature review and field study. The aim of the background questions was to provide a qualitative analysis of the two topics – SCM philosophy and BIM technology – regarding theory (literature review) and practice (field study). The two background questions, which further set the ground for the subsequent key questions, are:

– **RQ#1: What design and construction challenges of the AEC industry could the SCM and BIM concepts potentially manage?** (Chapter 2)
– **RQ#2: What are the interdependences between BIM technology and SCM practices in real-world settings?** (Chapter 3)

The previous questions provided the tools to create a preliminary conceptual synthesis of the two research topics: SCM philosophy and BIM technology (*description* part). The key questions of the research used the interim conclusions developed during the *analysis* part of the research. Both "what" and "how" questions were considered. The "how" questions were answered by a quantitative and applied research approach and provided the main research products: (a) the theoretical synthesis and (b) the proposed operational framework. The "what" questions were answered in a mixture of qualitative and quantitative approaches for providing grounded insights into the causalities observed in real-world case studies. The last "how" question (RQ#6) introduces the *synthesis* part of the thesis. The key research questions are the following:

– **RQ#3: How to combine the SCM with BIM concepts to analyse BIM-enabled SC partnerships?** (Chapter 4)
– **RQ#4: What are the effects of BIM-enabled SC partnering on the formal and informal relations of the Supply Chain?** (Chapter 5)
– **RQ#5: How does BIM impact the intra- and inter-organisational relations of BIM-enabled SC partnerships?** (Chapter 6)
– **RQ#6: How could the BIM-enabled SC partnerships be shaped after the alignment of SCM philosophy with BIM technology?** (Chapter 7)

§ 1.4 Research methodology

§ 1.4.1 Research design

This research has been conducted at empirical and theoretical levels to address issues of technology implementation, management, integration, and organisational dynamics. Golicic et al. (2005) explained how there is a need for a more balanced approach between "inductive research methods (typically qualitative) in addition to deductive methods (typically quantitative) in Supply Chain Management." The focus of the research is pragmatic – i.e. theoretical and practical – thus, a mixed method was undertaken. The mixed approach entails both inductive and deductive reasoning as well as both collection and analysis of qualitative and quantitative data. Dubois and Gadde (2002b, 2014) suggested a method that signifies an evolving intermediate interaction between inductive and deductive thinking, namely "systematic combining" or "abductive reasoning." The interaction between exploration (Chapters 3, 5, and 6) and theoretical experimentation (Chapter 4) would provide the final research products: a theoretical synthesis and a model to describe BIM-enabled SC partnerships and foster the potential popularisation of BIM and SCM.

The overarching research design was based on a set of four interdependent studies of five case studies. The case study methods were selected for offering rich insights into the emerging phenomenon of BIM-enabled SC partnering. The exploration was facilitated by the observation of real-world phenomena (Chapters 3 and 6), and the theoretical experimentation (Chapters 4 and 5) was facilitated by devising a modelling method for the analysis of the mechanics of the real-life BIM-enabled SC partnerships. Input from theory in the areas of SCM, BIM, Social Networks, and Modelling, were combined with input observed in practice so as to project a potential future state of AEC, where SCM practices and BIM technology could mutually support each other. The theoretical and practical inputs were concurrent, i.e. all research chapters (from 3 to 6) contain both theoretical and empirical insights. Figure 2 illustrates the interaction among various lines of thought undertaken in the study.

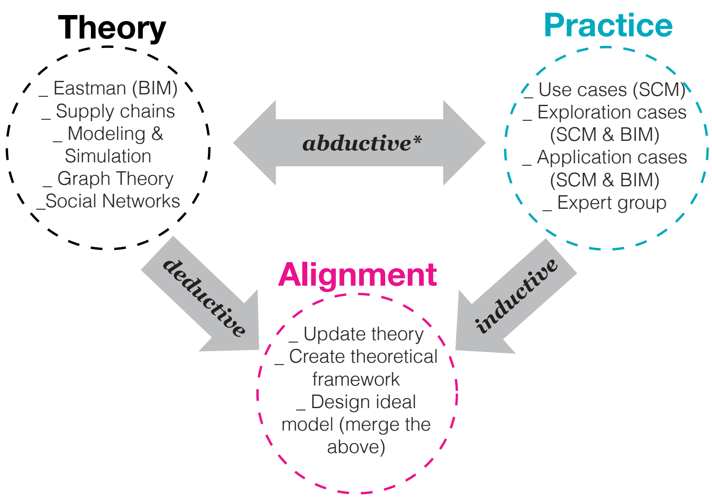

FIGURE 2 Mixed approach: The interplay between theory and practice. *Adopted from (Dubois and Gadde, 2002).

§ 1.4.2 Research methods

The diverse character of the two main research topics, SCM philosophy, and BIM technology called for diverse research methods for each topic. Various research methods were used to respond to the research questions, which amounted to 'mixed methods'. The research analysed both qualitative and quantitative data. The qualitative part included literature analysis and exploration of the status of BIM adoption within existing real-world SC partnerships, where SCM was applied, i.e. RQ#1 and RQ#2. The quantitative part proposed a modelling analysis tool analysing BIM-enabled SC partnerships (RQ#3) and subsequently applied its underlying modelling principles to two real-world cases for analysis (RQ#4). Additional empirical case analysis also took place (RQ#5). The two parts were concurrent from the third year onwards. The interim results from each part were informing and shaping the other part. Finally, based on the previous research questions and findings, the synthesis of the two topics had a theoretical and prescriptive character (RQ#6). Particular attention was given to the establishment of a balanced research for both BIM and SCM concepts.

First, the research was based on the exploration of the existing literature about SCM in construction and BIM technology. During that period, the initial theory development (deductive decisions) took place (RQ#1). Second, the exploratory case studies were selected for providing a "real-life context" and inductive character to the research (Yin, 1984) (RQ#2). The exploration phase, based on case study research, could have been approached by three different possible scenarios. The explorations would offer the basis for a structured comparison among various projects to reveal the interactions of

BIM-based technologies and SCM practices. The three possible scenarios for selecting the cases were:

- Comparison among BIM-based projects *without SCM implementation*, with the ultimate goal, to examine the compatibility of SCM philosophy with BIM. This option could be supported by plenty of BIM-based projects worldwide.
- Comparison of integrated SC partnerships *without BIM implementation*, with the ultimate goal to examine the compatibility of BIM with the SCM philosophy. This option could be catered by plenty of opportunities in the Netherlands, and potentially be explored to other industries.
- Comparison of *SCM practices with BIM implementation*, with the ultimate goal to investigate, register and consider alternatives for further integration. This scenario entailed a great challenge as to the case recruitment process because the BIM-enabled SC partnerships were quite rare (at the time of the study), and mostly available in the Netherlands (see also sections § 3.3 and § 8.1).

From the three scenarios, the third was followed, although it was the most challenging regarding the availability of case studies. First, the added value of the third scenario was that it combined both research topics (SCM and BIM) and thus, various nuances of the simultaneous real-world use of SCM and BIM could be observed. Second, any potential lessons learned from early and emerging forms of real-world SCM and BIM combination could reflect and provide useful insights into the future state of the AEC industry. A sample of five case studies and around 40 involved and inter-connected firms was finally recruited for the study. Although the sample of cases seems quite small, it is comparable to the amount of cases studied in other construction management-related PhD dissertations in the MBE department, such as of Vrijhoef's (2011) and Bektas' (2013), who followed nine (isolated) and two cases respectively for the exploration of supply chain integration and knowledge management correspondingly.

The case studies played a dual role in this research: exploration and application. On the one hand, the case studies provided an array of possibilities for iterative improvement, validation, and verification of the research questions and hypotheses (exploratory case studies for RQ#2). On the other hand, the case study research was a "natural complement" (Eisenhardt & Graebner, 2007) to the deductive modelling explorations. The modelling approach was followed to analyse the case studies by using background knowledge from both SCM philosophy and BIM technology (RQ#3). The quantitative model was applied accompanied from qualitative data analysis in a real-world setting of two cases to explore the research questions (application case studies for RQ#4). The same cases were followed to answer RQ#5. The interaction between exploration and theoretical experimentation provided the final research product: the synthesis of an operational model to describe the future BIM-enabled SC partnerships (RQ#6). Finally, RQ#6 entailed the theoretical synthesis and the construct, i.e. on methodology, internal, i.e. from the case participants, and external, i.e. from an expert panel, validation steps. These three validation steps were sought, because the thesis is at the intersection of social science, management, and engineering and the main two constructs, BIM and SCM carry different connotations for each field. Explicit information about the research design and the exact methods used to respond to each research question are included in the respective chapters (3 to 6). Figure 3 illustrates the above relations between the research questions and case studies.

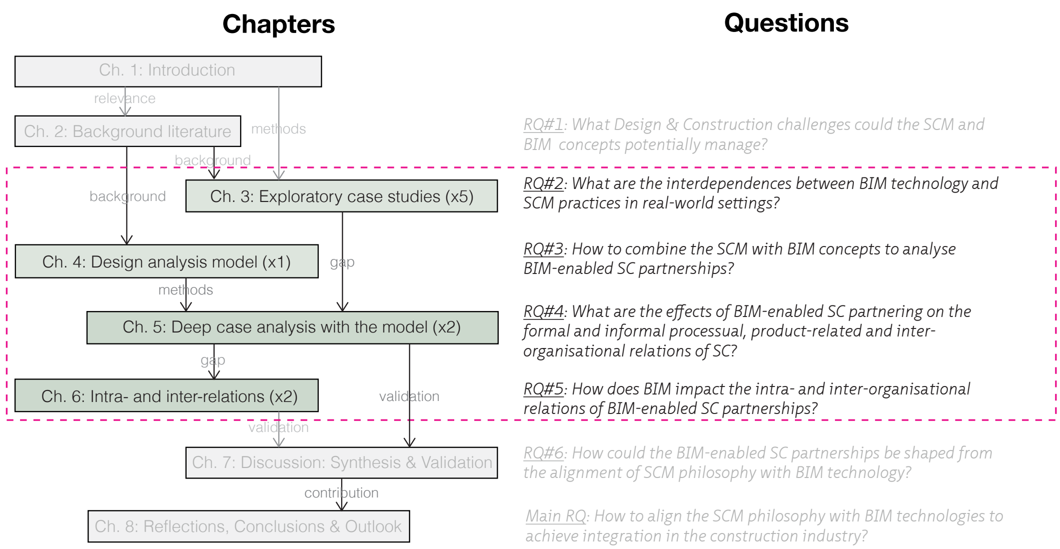

FIGURE 3 Relation between the chapters and research questions. The red dashed line includes the case studies and the parentheses indicate the number cases per chapter.

§ 1.5 Research impact

§ 1.5.1 Relevance of the research

The research impact has been considered as to its relevance and limitations. The relevance defines the aspects that the research pertains. The limitations underline the boundaries of the research. This section first presents the relevance of the thesis as to four categories: regional relevance, which is emphasised by the study of cases only in the Netherlands, societal relevance, relevance to practice and relevance to science.

These aspects were further examined to demarcate the necessity for this research as well as the areas where it could be directly applicable.

Regional relevance

The Dutch construction industry was selected as the ground for these empirical explorations with the ultimate goal to generate theory on the combination of BIM technology and SCM practices. Ozorovskaja et al. (2007) claim that the Netherlands represent a model of West European managerial values and practices, which although cannot be generalised, certainly play a cultural role in Europe. The Netherlands was a relevant setting for this PhD research because it is a reactive, progressive, and highly influential market to its neighbouring countries. Three main reasons explain this selection: the (a) attention given to partnering and SCM practices, (b) affinity to innovation regarding construction IT, and particularly BIM, and (c) idiosyncratic characteristics, e.g. risk aversion, of the Dutch market that allows for scalability and generalisability of the observations. Wamelink and Heintz (2015) explain how keen the Dutch construction industry has been to adopting innovations that are integrative in nature, e.g. IPD, BIM, and SCM. The following paragraphs explain the longevity of SCM in the Netherlands, the current advanced level of Dutch BIM maturity and the characteristics of the Dutch construction industry respectively.

Supply Chain thinking in the Netherlands has followed the corresponding shift that took place in the UK (Vrijhoef, 2011). The *Rethinking Construction* movement for the UK construction was initiated after the publishing of the *Rethinking Construction* Report from Sir Egan (1998). This movement was sponsored by the government and formed a set of general suggestions to the practitioners of the UK construction. The scope of these recommendations was to ignite change in the construction industry regarding: (1) committed leadership, (2) customer focus, (3) integrated processes and teams, (4) quality-driven agenda and (5) commitment to people (Egan, 1998). Four key actions were identified, to attain these goals, as to (1) product development, (2) project implementation, (3) partnering the supply chain and (4) production of components (Egan, 1998). According to Vrijhoef (2011), the Dutch building industry followed these suggestions seven years later, by focusing on reducing waste, engaging in partnering and focus on collaboration and integration of actors. Whereas there is an abundant scepticism on SCM in the UK (Briscoe & Dainty, 2005; Fernie & Tennant, 2013), it nevertheless seems that SC thinking has been compatible with the culture in the Dutch construction industry.

Netherlands has also been a forerunner in BIM adoption. BIM maturity at a national level could be evaluated in various ways. From a market perspective, reports such as from McGraw-Hill (2014) that conducted research among 727 contractors from "*ten countries that represent some of the largest construction markets globally: Australia,*

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Brazil, Canada, France, Germany, Japan, New Zealand, South Korea, UK and the United States" do not include the Netherlands, due to the small economy size. However, in academic research, the Dutch market has been research-worthy concerning BIM. Kassem et al. (2015) rationalise the BIM maturity of countries based on their policy, e.g. as to issuing guides, protocols, and mandates. They analysed "*publically available documents (...) intended to promote BIM understanding, regulate BIM implementation or mandate BIM requirements*", from countries such as the Netherlands, Denmark, Finland, Norway, and Singapore, who have not been traditionally considered precursors of innovation in construction. Their findings suggest that BIM in the Netherlands is well developed and balanced as to the distribution of both suggestive and mandatory documents (Kassem et al., 2015). Thus, it could be a locale worthy of BIM-related explorations.

The regional relevance and the target audience of the study are underlined by the firms that participated. Apart from the firms that participated in the case studies, industrial experts that did not play a role in the research carried a validating role for the research validation (Chapter 7). Eventually, five case studies of BIM-enabled SC partnerships in the Netherlands were followed. The researcher was not affiliated to any of these firms, and should be considered objective. Given that the participating firms generously provided proprietary data for research purposes, their identities remain anonymous throughout the thesis.

Societal relevance

The research has a grave societal relevance, based on economic criteria, relevant to SCM, and political and educational decisions, relevant to BIM. Nowadays, the main flows of the construction SC, i.e. information and material, are weakened, and this fact causes loss of time, cost and material. Time and cost fallouts and overruns, material loss and excessive waste are some of the consequences, as described in sub-section § 1.2.1. At the same time, the unstructured image of the field encourages the transactions in grey money with apparent losses to the state's revenue. The economic crisis of 2007 magnified the problems above. It resulted in jobs losses and brought the profit to a minimum. For example, in the Netherlands, about fifty thousand positions in the AEC were lost because of the financial crisis (Rijt et al., 2010). At a first level, the AEC firms have recognised that their engagement in SCM practices improves their business survival rate simply by increasing their chances to be active through these collaborations. In the long run, these benefits also slowly would become financial. Regarding BIM, it has already been recognised as a profitable investment (McGraw-Hill, 2014). And as every difficulty is an opportunity for growth, shedding light on innovative approaches in construction is necessary for the survival of not only small or medium but also larger enterprises, where the impact of any change is proportionally higher.

Since the introduction of BIM, it has been the focus of several national policies in their effort to facilitate the technological shift in the building sector. Numerous national bodies have recognised the potential of BIM for optimisation in construction. For example, the UK, Scandinavian countries, USA, Australia and Singapore have already issued BIM-related guides, protocols or mandates (Succar & Kassem, 2015). Consequently, new and specialised guidelines appear regarding requirements, design processes, contracts, and deliverables of BIM. Whereas SCM practices are quite vague and usually not formally described at a national level, the numerous norms, templates, and directives on BIM implementation in the Netherlands support the regional relevance of this research.

The growing adoption of BIM, suggests a shift in the construction industry. In the past, the construction industry was considered quite slow in the adoption of new technology (Davies & Harty, 2013). However, in most countries, nowadays BIM is already a standard qualification for work positions in AEC. In the Netherlands, the use of BIM is made largely compulsory by the Government Building Agency (GBA) (Rijksgebouwendienst, 2012). Germany is also currently preparing similar mandates for BIM implementation (BMVI, 2015). Soon, the European Union will also adopt one of the produced National mandates. The above has an underlying societal impact. Given that the AEC transforms in a rapid pace, the young professionals entering the field, need to be educated with the latest developments, so as to be competitive and employable. Therefore, although the BIM area of research is in transition, the education curricula for the AEC professionals could be consciously and globally designed, without interrupting the amount of novices entering the field, and at the same time, addressing valid and scalable topics.

Practical relevance

Given that the increasing amount of BIM mandates would subsequently affect all the various AEC practitioners, the SCM philosophy is highly relevant to managing the complexity of the emerging inter-organisational relations. The aforementioned national efforts for standardisation may also mandate the adoption and implementation of BIM by requiring the obligatory application of BIM apart from the design stage to all four main phases of the project lifecycle, i.e. from initiation to design, construction, and operation. Moreover, presently more and more professionals are engaged in SCM and particularly the initiators – either clients or construction firms – focus on apart from new construction to renovation building projects. Thus, with a potential spread of BIM-enabled SC partnering, there is an opportunity to extend the applicability of BIM technology from the design stage, which is currently the most popular application (Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013), to the construction, operation, and maintenance stages of the AEC lifecycle.

In theory, the research on innovative socio-technical approaches is required now more than ever, but in practice, not all participating actors of the AEC industry are willing to adjust or change their business models and strategies by adopting new theories or technologies, such as SCM and BIM respectively. However, the current diffusion rates of both SCM practices and BIM technology indicate that they would be probably a standard requirement for the future AEC professions, from top managers to unskilled personnel. The AEC firms are thus greatly interested in investigating the exact profitability and usability of them. This research attempted to support the necessary underlying managerial shift and prepare the AEC organisations for the application of integrated theories, practices, and tools in construction. Ultimately, even through difficulties and managerial changes, the organisations of AEC would transit from an unprepared and rigid structure to integrated practices along with SCM applications and BIM adoption. After all, "competition is shifting from firm versus firm to supply chain versus supply chain" (Vonderembse, Uppal, Huang, & Dismukes, 2006) and the organisations would be consciously steered into optimising their chains organisationally and technologically.

Relevance to science

With this thesis, a refinement of both constructs of BIM – for being an emerging concept – and SCM – for being an ill-defined concept – has been attempted. The research on BIM encompasses all efforts that begun around the 90s to ensure a structured representation of building project information (Eastman, 1999). However, this research topic is relatively new and understudied, from an inter-organisational vantage point (Adriaanse, Voordijk, & Dewulf, 2010b; Dossick & Neff, 2010). This research approaches BIM as an integrated data structure of building information without focusing on standardisation issues, software suites or any particular tools. *This thesis acknowledges that BIM cannot present a panacea for collaboration in the SC, and estimates that when in the future a similar building product model, or another similar type of construction IT, will be deemed as more appropriate, this thesis would remain relevant because it combined the promise of object-oriented modelling, in this case of BIM (or any other similar technology) for structurally representing building information to a set of practices for inter-organisational collaboration, i.e. SCM and partnering*. At the same time, this research reflected and revisited the theory on SCM by combining it with previously neglected concepts of 'human agency' (Green, Fernie, & Weller, 2005; Fernie & Tennant, 2013), and contemporary IT tools for information management, such as BIM.

Apart from contributing to the SCM philosophy and BIM technology separately, their combination has been unique regarding conceptualisation and methodological approach. Product-oriented modelling, i.e. BIM, and SC thinking have been previously defined as compatible approaches. Nederveen et al. (2010) suggest that the existing “top-down, (...) tailor-made approach will be replaced by more market-driven, bottom-up organised, integrated supply chains that develop product families” in the future. This research apart from promoting their theoretical and practical link aims to contribute to the theoretical base of both research topics by redefining their properties based on their common ground: the information flows. Moreover, it had a prescriptive and potentially educational character by analysing and synthesising how SCM and BIM concepts are combined in practice so as to not only support the research on those topics but also provide a real-world context for educating future professionals.

§ 1.5.2 Limitations

The research limitations are found in four aspects: (a) geographical restriction, (b) type of projects included in the case study, (c) focus on the ‘supply’, rather the ‘demand’ side, and (d) recognising but not further considering SCM practices in other industries, such as the manufacturing. One of the most obvious research limitations was that all the studied projects were located in the Netherlands. Apart from the regional relevance, which was described previously in sub-section § 1.5.1, the explorations in the Netherlands were favoured for reasons of proximity and manageability of this doctoral research project. Nevertheless, understanding the particular features of the Dutch construction industry has been essential for projecting and attributing the research findings to other construction markets. Whereas this research cannot be directly generalised to other countries, it could simulate chains and projects with high degree of repetition, and also project to a future state of higher supply chain integration through partnering as the Egan report (1998) had envisaged.

The research focused on building projects, whereas some of the final conclusions could be relevant to infrastructure projects. No limitation was imposed on the type of building projects during the case study recruitment and selection. The real-world case studies that were central to the second part of the research (synthesis part) are housing, multi-functional (housing plus commercial and offices), and utility complexes (offices and small factories). No limitation was set concerning the scale of the projects either. However, no mega-project was made accessible or studied. Also, although SCM and modular approaches to house building have been deemed as a “promising way forward” (Halman, Voordijk, & Reymen, 2008), and this could be probably aligned to the use of BIM, no such projects were recruited as cases as well. However, this limitation was not necessarily a weakness of the research, given the fact that most AEC companies first start to experiment with new theories and practices from small and medium projects and subsequently attempt to build up their skills and readiness incrementally to more demanding and prestigious situations and projects.

The phases and actors that are studied in this research are related more to the 'supply' side of the AEC industry. This phenomenon took place due to a lack of a local industrial network to provide access for varying cases studies, given that as mentioned above, this thesis has had no specific 'problem-owner' (see section § 1.1). Only a few considerations were given on the 'demand' side, regarding the clients and occasionally the users or the facility managers of the studied projects. The research examined the interaction of SCM philosophy and BIM technology from the initiation phase, through design and construction to operation phase. Concerning the involved actors, the research involved the client and the tendering team, the design and construction team, as well as certain suppliers (depending on the studied project). Whereas these boundaries were first set during the literature review and the *analysis* part, during real-world exploration, it greatly depended on the availability of these phases and SC actors in each case study. Exceptions are possible, e.g. most cases did not have an a priori facility maintenance vision, or in one instance the tenant (user) was involved from an early phase in the design reviews.

Presently, other industries apply SCM practices and tools for advanced IT, such as Enterprise Resource Planning (ERP) or e-procurement systems, that attempt to merge the product information (which in the present research could be related to the product breakdown structure offered by the BIM applications) with the business process planning. However, such applications, from e.g. the manufacturing or the retail SC, cannot be directly transferable to the AEC SC. The high demand variability, high variability and the delivery cycle time variability make it difficult to implement these approaches. Therefore, the social features of the network, regarding the organisations, and the interactions among the actors were taken into account instead. The originality of this research lies in the fact that most approaches to SC research in AEC focus on material, costs and process simulation, e.g. logistics, but not on the interactions among the various involved actors, and particularly from a network perspective, which is the case in this thesis.

§ 1.6 Thesis structure

This dissertation would answer the central research question through the next seven chapters. The thesis has three parts: *description*, *analysis*, and *synthesis*. The *description* part includes the introduction, background, and the exploration (Chapters 1, 2, and 3). In this introductory chapter, the problem statement, research objectives, questions, and impact have been explained. Chapter 2 focuses on the research background and establishes the context, scientific gap, and the necessity of this study, i.e. the theoretical and conceptual framework. It contains a literature review to answer the first background question and defines the Design and Construction challenges that could be potentially managed from the combination of SCM philosophy with BIM technology. Chapter 3 is also a background chapter but from the practical side. The third chapter has answered the second background question and explored various constellations of BIM-based SC partnerships. It presents the qualitative analysis of the cases (exploration) and explains the changes in the processes and roles due to BIM technology within five integrated SC settings. Given that Chapter 3 was largely empirical, is also hereafter called: 'empirical exploration'.

The second part of the dissertation, i.e. *analysis* part, contains the research findings and the reflection upon those. Chapter 4 has responded to the first key research question and deployed quantitative research and analysis methods so as to combine SCM and BIM concepts. Chapter 4 is also hereafter called: 'conceptual exploration', given that it is primarily based on conceptual experimentations and a proof-of-concept case. This analysis tool for BIM-enabled SC partnerships was further applied to two real-world cases subsequently. Chapter 5 contains the application part of the developed model to analyse two *polar* case studies and answers the second key research question by featuring an analysis of BIM-enabled SC partnerships. Chapter 5 is also hereafter called: 'pragmatic exploration' because it is found at the intersection between conceptual and empirical explorations. The developed research method for Chapter 5 merges the two SCM and BIM concepts to integrate organisations, processes, and products and analyses the mechanics of BIM-enabled SC partnering in a real-world context. In Chapter 6, additional empirical explorations in conjunction with a theoretical SC model took place. Given that the analyses in Chapter 6 were based on a theoretical framework, Chapter 6 is hereafter called: 'theoretical exploration'.

The third and last part of the thesis is about *synthesis* (Chapters 7 and 8). Chapter 7 contains the synthesis and discussion in the form of research validation. There, the findings from the various explorations of Chapters 3 to 6 were confronted with literature and combined during (a) the synthesis of the theory and (b) the suggestions of strategies to further integrate the SCM and BIM concepts and answer the last key research question. Chapter 8 recapitulates the findings, presents the research conclusion, and suggests directions for further research. Figure 4 shows the relation between the parts of the thesis (*description*, *analysis,* and *synthesis*), chapters, research questions, and products generated from each knowledge field, i.e. theory and practice.

In Chapters 2 to 7, the answers to the RQs are highlighted with *italicised* text in the concluding sections § 2.8, § 3.6, § 4.7, § 5.6, § 6.6, and § 7.7, respectively. Also, as Chapters 3 to 6 are largely based on five published and in revision conference papers and journal articles, where necessary, the relations among these chapters and publications are indicated with a footnote at the beginning of the chapter. The first author – and researcher – is the main contributor to these publications (about 95% contribution). At the same time and because these chapters are largely based on journal articles, some redundancy may be found between the 'introduction' and 'methodology' sections of Chapters 3 to 6. However, the benefit of included work from published journal articles and conference papers is that theresearch presented in this book has undergone multiple rounds of blind peer reviews. This is a conscious choice with the intention that these chapters could 'stand-alone' as independent studies. Whereas each of these chapters follows a different methodology, some repetition takes place in the methodological rationales. Before each chapter, an indispensable 'chapter summary' is used to help the reader connect the chapters logically.

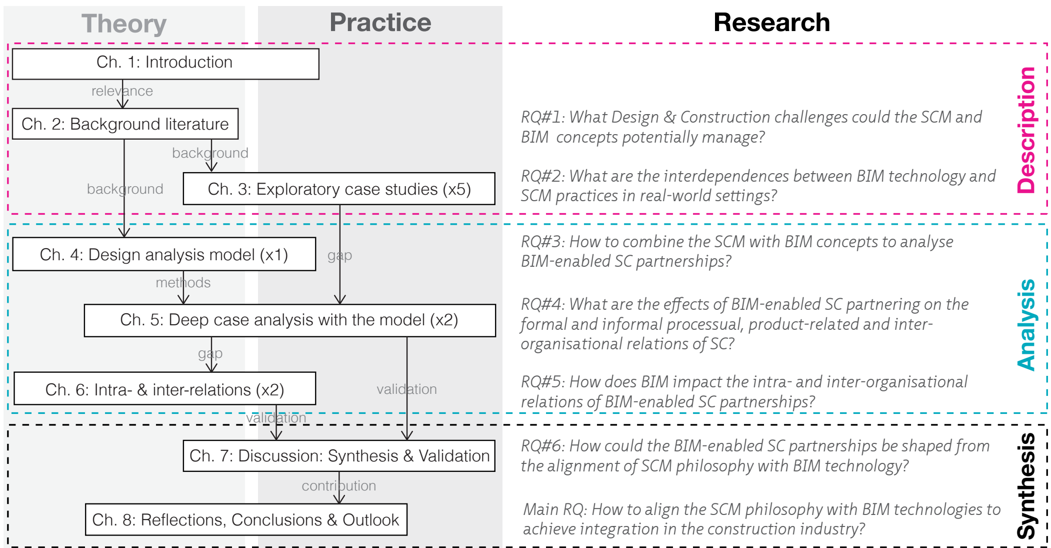

FIGURE 4 Parts, chapters and research questions of this thesis per knowledge field (theory and practice).

§ 1.7 Chapter recapitulation

This chapter described the motivation, background, relevance, and strategy of the thesis. Initially, it explained the research background as well as the personal motivation for undertaking this study. The introductory chapter emphasised the need to explore innovative theories and technologies so as to optimise the SC flows in AEC. The research rationale is the combination of SCM philosophy with BIM technology for achieving SC integration in the building industry. The relevance and the limitations underlined the practical boundaries of the research. The aim of this thesis is apart from exploring the current state of construction through the lenses of SCM philosophy and BIM technology, to propose an analysis tool for their optimal evaluation and combination. These two primary goals would be achieved by the combination two main research approaches. The first part, i.e. *description* part, contains qualitative data and information, from literature review and analysis of real-world examples. The a*nalysis* part also contains some quantitative data and information and features mixed research methods. The last two chapters contain the *synthesis* part, which entails (a) the theoretical synthesis of the research and (b) a set of strategies for future BIM-enabled SC partnerships. This introductory chapter finally contained the overall outline of the thesis, as well as a guide to the reader.

2 Challenges in Design and Construction Management

Chapter summary

The background chapter connects to the introduction (Chapter 1), by further expanding on the used concepts and definitions and offering an additional elaborate theory on them, and particularly on the design and construction challenges that SCM and BIM concepts could potentially manage (RQ#1). This critical review underpins the conceptual link between the SCM and BIM constructs. The two areas have been reviewed in a semi-chronological order, as a 'challenge and opportunity' scheme, starting from SCM (in the 1950s), and then proceeding to BIM (1980s). First, the challenges pertinent to Design and Construction Management in AEC industry are presented. Advancements related to Supply Chain thinking have already delivered significant improvements in the efficiency and effectiveness of other sectors, e.g. the manufacturing. However, the pragmatic impact, i.e. the practical consequences, of applying SCM philosophy in construction has been debatable over the years.

To this end, object-oriented modelling – and particularly BIM – is suggested as a potential technology (IT) to regulate the information flows. The origins of BIM are found in the long-lasting efforts to standardise the building information through product modelling, from a 'bottom-up' approach, i.e. software companies, industry consortia, and construction researchers. At the same time, many efforts to standardise BIM have been made, but from a 'top-down' approach as to the delivery and the collaboration processes in the form of National mandates. The observed mismatch between the bottom-up and top-down strategies to popularise BIM could be potentially coordinated by focusing on structured multi-disciplinary environments, and the analysis of their inter-organisational relations, e.g. by focusing on SCM philosophy and SC partnerships. The dimensions of process, product, and actor (P/P/A) are accordingly defined as the common ground for both SCM and BIM concepts. The research gap is then established as to the fact that in both SCM and BIM relevant research, the deployment of an inter-organisational standpoint from a network perspective has not been previously held regarding product-related, processual, and organisational aspects.

§ 2.1 Challenges in the management for AEC

§ 2.1.1 Complexities and fragmentation in construction industry

The AEC has been considered an extremely complex industry from various perspectives and for different reasons (Azambuja & O'Brien, 2009; London, 2009; Vrijhoef & London, 2009). Complexity relates to the existence of numerous or infinite components and inter-relations that compose a system (Mitchell, 2009). Complexity in this study is not to be confused with understanding and managing complexity at a project level (Bosch-Rekveldt, 2011), rather than is focused on complexity as a ubiquitous phenomenon in the construction industry. Winch (1998) identified high inter-connectedness, unpredictability and high user involvement in the innovation process as traits of a complex product system, such as the AEC industry. Complexity is a multi-faceted property and could refer to various aspects of the industry. Complexity concerns (1) technical product complexity, due to the inherently complex design and construction processes (Gidado, 1996; Dulaimi, Ling, Ofori, & De Silva, 2002), (2) operational or processual complexity, from the rigidities that develop along the various operations (Gidado, 1996), and (3) organisational complexity, which relates to the vast amount of the involved multi-disciplinary organisations (Nam & Tatum, 1992). Christopher (2011) further added network, range, customer, supplier and information complexities to the above. AEC has additionally been susceptible to contextual complexities, due to external uncertainties, e.g. from the natural environment (Winch, 2002, p. 80). At the same time, given that other industries are also inherently complex but well-performing, complexity might not be the sole reason for the under-performing and weak image of AEC industry.

Fragmentation is another metric – complementary to complexity – which refers not only to the multiplicity of actors but also to corrupted, broken, loose, non-existent inter-relations or linkages among them. Fragmentation concerns the problematic relations among the various functions or actors of the project. It usually refers to the construction industry, which has been seen as fragmented into its constituent parts, e.g. numerous Small and Medium Enterprises (SMEs) (London, 2009). This fragmentation is a source of additional complexity and, therefore, a challenge. Fragmentation relates mostly to the structure of the industry, and particularly to the high number of work specialisations involved, the low interdependency among them, the local character of most projects (Azambuja & O'Brien, 2009). Howard et al. (1989) described this phenomenon as a lack of "horizontal integration" among the various project specialists. Bruijn and Heuvelhof (2008, p. 2) noted that the rising professionalism automatically means more fragmentation for the organisations and their inter-organisational relationships. Fragmentation could also relate to the lack of continuous functions and processes, which is caused and enhanced by the single-project focus. Nam and Tatum (1992) further differentiated fragmentation to the lack of vertical integration of the actors in a project, i.e. project disintegration. Given that this thesis has focused on inter-firm relations, fragmentation refers to that disintegration of organisational structures.

Based on the above two metrics of complexity and fragmentation, the construction industry is usually compared to the manufacturing sector, given that it produces equally complex projects with high technical complexity. Despite presenting equivalent complexities, the manufacturing sector is far more restricted in location and less fragmented as to the number and type of the various participating firms. Vrijhoef (2011) suggested that the high degree of repetition has a causal relation to the integration that attests in the manufacturing industry. Given that the construction sector has high demand, time, and circle variability, repetition could be achieved either through industrialised construction or via repetitive projects. Dubois and Gadde (2002a) pointed out that the single-project focus of the AEC industry is responsible for the above complex image. They also claimed that the single-project focus of construction and the temporary couplings among the various firms further hinder organisational learning and innovation (Dubois & Gadde, 2002a).

§ 2.1.2 Advancements from other industries applicable to AEC

It would be valuable to examine how other industries have dealt with similar challenges in the management of technical, processual, and organisational complexities. Dubois and Gadde (2002a) highlighted that "management techniques that improve performance in other industries are not readily transferable to this context", i.e. AEC. The thesis avoided comparing directly various industries with one another. On the contrary, only the impact of specific advancements from the manufacturing, retail, and commerce, aerospace and automotive industries was studied. These advancements or approaches – on either theory or technology – have been presented semi-chronologically starting from Operations Management research, lean and agile approaches, electronic procurement (e-procurement) systems and product development, and modular design. Some of these concepts and applications present an inherent affinity or are already coupled with Supply Chain Management and Building Information Modelling. Therefore, the short review of these approaches aims to increase the understanding of the afore-mentioned complexities, and not to promote particular innovations native in other sectors. Moreover, these innovations were selected because they have been considered compatible, complementary or precursors of the SCM philosophy and BIM technology.

Operations Management

The AEC industry is usually described regarding efficiency and effectiveness, from a processual aspect. Efficiency is a combination of reduced costs and smaller cycle times. In Operations Management (OM), the cycle time of a process is composed of capacity, utilisation, and variability (Cachon & Terwiesch, 2009). From a managerial point of view, this variability is of major importance, being "the primary factor that influences the parametrisation of a process", according to Reiner (2005). The OM research was developed after the 1950s to cover the need for scientific approaches in business research. The development of OM coincided with the positivistic philosophy of science, according to which "the phenomenon under study can be isolated from the context" (Meredith, Raturi, Amoako-Gyampah, & Kaplan, 1989). Nowadays, concepts from OM have had already been suggested as potential tools to analyse the construction SC (O'Brien, London, & Vrijhoef, 2002). Construction Management (CM) research has been already largely benefited from OM research because either in single- or multi-project focus, i.e. SCM perspective. Currently, several repeated operations of AEC could be controlled via quantitative analyses, for example, scheduling, inventory analysis, and cost estimation, straight from the toolbox of OM research.

Lean and agile approaches

Other advancements for controlling the processual complexities in the manufacturing that additionally apply to AEC are lean and agile methods. Lean construction refers to the "adaptation of the underlying concepts and principles of the Toyota Production System to construction" (Sacks, Dave, Koskela, & Owen, 2009). The fundamental attention of lean construction is to reduce waste, increase customer value and attain continuous improvement. The lean approach requires, again, low variability to perform as well as it does in manufacturing. Thus, it is not applicable to AEC, due to the high demand variability, supply variability, and delivery cycle time variability. On the other hand, agility refers to "using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place" (Naylor, Naim, & Berry, 1999). In construction, agility focuses on developing flexibility and responsiveness in the construction process – especially during the delivery phase – and "a response to complexity brought about by constant change" (Sanchez, 2001). In contrast to lean construction, the agile approach is suited for high product variability and allows inventory to respond faster to the market demands. Lean has also conceptualised the work collaborative structure as a production system design (Ballard, Koskela, Howell, & Zabelle, 2001), which could potentially engage the project team to faster and responsive collaboration patterns and generate maximum value for the end-customer.

Electronic-Procurement systems

The advent of technology in the delivery systems of construction industry echoes the innovative systems used in the procurement of goods in the retail and commerce sectors. With the support of IT, and particularly of data and object modelling techniques, the Electronic Business (e-Business) processes are employed by the organisations not only internally but also externally in collaboration with their partners, so as to regulate both the technical and processual complexities. Among the benefits of Electronic Procurement (e-Procurement) are significant savings in the acquisition process, alignment of all the suppliers, faster, continuous and easier acquisition of goods, the combination with ERP-systems and elimination of rework, smart-tagging such as Radio-Frequency Identification (RFID) and Near Field Communication (NFC) and accurate predictions. Recently the smart-tagging technology coupled with Geographic Information System (GIS) have become a widespread practice in the construction sites as an effort to minimise material losses and rework and control the technical, and processual complexities.

Product development and modular design

Another direction is the thinking in products rather than projects, similarly to the aerospace and automobile industries. This approach relates to industrialisation by mechanisation and automation and could deliver further integrated products as to not only efficiency and effectiveness, but also as to the integration of the expertise of various disciplines in one confined and consistent building product. These concepts have most successfully adapted from the AEC industry. For example, platform strategy promotes product modularisation – usually via prefabricated components –, interchangeability and standardisation and distributed production systems (Halman et al., 2008). These approaches imply a decentralised and not centralised design and engineering control as in the aerospace and automotive industries (Vrijhoef, 2011). The industrialised modular approaches to house building have been deemed as a “promising way forward” (Halman et al., 2008) as to dealing with the technical, and processual complexities, yet they do not respond to the product or demand variability that is inherent in construction and could also hinder creativity for AEC. Moreover, despite requiring the pertinent involvement of many organisations, these approaches do not “necessarily imply long-term and strategic supply chain arrangements (...) remain relatively operational” (Vrijhoef, 2011) and do not reform the fragmentation of construction beyond instantaneous benefits.

§ 2.1.3 Remaining complexities and fragmentation in AEC

The previous theorisations and practices in the manufacturing, retail, commerce, aerospace, and automotive industries, suggested a set of approaches potentially compatible with construction management research. Namely, the use of quantitative analyses from OM, the focus on reducing waste, the tracking of the material flows and the connection between product requirements and product specifications, have been adopted to some extent by the AEC industry. Table 3 illustrates the applicable complexity and fragmentation areas that these approaches could improve. However, all of these approaches do not manage to reduce all the inherent fragmentation and complexity of construction.

TABLE 3 Complexities in AEC and in which extent advancements in other industries have tackled them.

	PROCESSUAL COMPLEXITY	TECHNICAL (OR PRODUCT-RELATED) COMPLEXITY	ORGANISATIONAL COMPLEXITY & FRAGMENTATION
Operations Management	x	-	-
Lean and agile approaches	x	-	x
e-Procurement systems	x	-	x
Product development & modular design	x	x	-

Based on the above, this chapter aims to reveal to what extent the topics under study, i.e. SCM philosophy, and BIM technology, manage the remaining complexities and fragmentation in AEC. At the same time, recently, the strategic focus in construction firms shifts from single-project considerations to multi-project focus. This further implies the transition from one-sided advancements to more holistic considerations for improving industry performance. After all, in other sectors, such as the manufacturing, commerce or automotive, the "competition shifts from a company orientation to a supply chain orientation" (Vonderembse et al., 2006) and this could be already the case for AEC. The main question of this section, therefore, is: *RQ#1: What design and construction challenges of the AEC industry could the SCM and BIM concepts potentially manage?* The next sections highlight how some of the above advancements or their features have been incorporated into SCM and BIM applications for the AEC industry.

§ 2.2 Origins and development of Supply Chain thinking in AEC

§ 2.2.1 The emergence of Supply Chain thinking from Operations and Logistics Research

London and Kenley (2001) place the emergence of Supply Chain related research in construction in the mid-1990s. In the manufacturing industry, the IT capabilities of the 1950s provided a fertile ground for the regulation and optimisation of the physical distribution of goods from raw materials to end products. From rationalising the processes of distribution and (later of) production, inevitably quality was improved, and this led to more strategic considerations for the procurement of products (Porter, 1985; Christopher, 1992). In construction, these manifestations followed a few years later, with emphasis on materials and cost management. From the early years, the positivist paradigm was already engraved, in Logistics and SCM Research on materials distribution and production. However, the positivist paradigm related to SCM Research lacked in external validity (Golicic et al., 2005). London and Kenley (2001) hypothesised that the future research on SC in the construction industry would move from "the rhetoric that it is a management tool to improve the performance of the industry," to "discussions of advantages of different types of networks, cluster or chain." To this end, Leuschner et al. (2013) have differentiated between the operational and relational view of SC integration in the SCM research field. Therefore, one might claim that SC thinking was already a concept in transition, drifting between processual and organisational aspects, by the time it was adopted in AEC.

In parallel, Supply Chains, have been described more as networks, rather than linear chains, from as early as 1998, by considering SC as a network of multiple business and relationships (Lambert et al., 1998). Christopher (2011) advocates that the word "chain" should be replaced by "network," given that the suppliers and the customers are accordingly connected to multiple other suppliers within this network. Accordingly, he proposes that it should be termed "demand chain management" rather than SCM since the SC should be driven by the market and not the suppliers (Christopher, 2011). The acknowledgement of the ill-defined grounds of SC thinking also comes from the acceptance that SC thinking is "part of an eclectic and developing hybridised field" (London & Kenley, 2001), despite being under study for more than 30 years (Chen & Paulraj, 2004). Chen and Paulraj (2004) divide the fragmented body of knowledge on SC concepts into three areas: (1) strategic purchasing, (2) logistics integration and (3) supply network coordination. From the above, it could be possible to conclude that the inter-organisational standpoints are also pertinent to SC thinking.

Whereas SC thinking emerged from OM and an entirely positivistic standpoint, the concept seems to have been evolving parallel to the shift in the leading philosophical paradigms of their eras respectively. When focusing on the networks of involved actors rather than the production and distribution of the materials, then inevitably the perspective is less positivistic per se – and potentially constructivist and interpretative[1] –, given that various viewpoints of the participating actors could also be taken into consideration. Thus, SC research could be considered an 'umbrella' term that greatly depends on the standpoint or the researcher, the Unit of Analysis (UoA) and the entity under study, material, actor or information. In this PhD research, SC thinking has been approached from a more interpretivist or constructivist viewpoint, by relying upon the perspectives of the various actors of the SC (Creswell, 1994). Despite been trained as an architect, the researcher attempted to minimise the impact of their background on the research and also did not assign the SC governance to a particular actor. To this end, the aim was to generate inductively a theory about the relations among the actors in the SC.

§ 2.2.2 Supply Chain Management concept in AEC

This thesis favoured the position of Lambert et al. (1998) who recommend that constructing a definition of SCM is easier than implementing it in real life. This thesis has aligned with Pryke's (2009) intention to demonstrate that SCM in construction is much more than a trend or a buzzword and could potentially contribute to added value for the client and the other stakeholders, beyond mere financial gains. Following the debate on the ambiguity of SC research in other industries, defining SCM in the context AEC is equally challenging. Notwithstanding, a few seminal frameworks for defining, analysing, understanding, and evaluating SCM in construction were used throughout this thesis for the analysis and synthesis of the relevant constructs.

In business research, SCM is defined as a holistic management approach to attain goals, such as increasing customer satisfaction, value, profitability, and competitive advantage (Mentzer et al., 2001). Mentzer et al. (2001) rationalise that acting upon the flows of products, services, information, fiscal resources, demand, and forecasts could reach the goals above. They left their findings open to interpretation and adaptation across different national cultures, types of firms or cultural variations (Mentzer et al., 2001). In construction, SCM has been mainly considered as the management of the three flows: information, material, and cash (Arbulu, 2009; Vaidyanathan, 2009). Other researchers further simplify these flows to only material and information flow (Cutting-Decelle, Young, Das, Anumba, & Stal-Le Cardinal, 2009), probably by considering cash flow as part of the information flow. Other researchers add and focus

1 See for example the Actor-Network-Theory, a primarily constructivist approach.

on an extended set of flows, e.g. material, labour, and equipment flow (Cox & Ireland, 2002). However, the comparisons and debates on the above fall beyond the scope of this thesis, because it has focused only on the information flow and further on the network of the various participating actors.

After defining and analysing the adaptation of SCM concepts in AEC, several researchers have attempted to evaluate the SCM practices. Lockamy III and McCormack, (2004) identify five levels of SCM maturity levels regarding process orientation and particularly co-ordination. Their taxonomy has been based on metrics related to predictability, capability, control, effectiveness, and efficiency (Lockamy III & McCormack, 2004). Accordingly, they characterise the Supply Chains, in decreasing order of maturity, as (1) *extended*, where competition lies upon the supply network – similar to the concept that competition shifts to SC orientation from Vonderembse et al. (2006) –, (2) *integrated*, with embedded process coordination, (3) *linked*, with some strategic process coordination, (4) *defined*, with basic process definition and coordination and (5) *ad hoc*, with ill-defined and unstructured processes (Lockamy III & McCormack, 2004). This framework and terminology have been used in this thesis as a basis for comparing various SC configurations.

In construction, SCM applies to multiple instances. Vrijhoef and Koskela (2000) define four roles for SCM in construction application as to (1) improving the interface between site activities and the SC, (2) improving the SC, as to its composition and expertise, (3) transferring activities from the construction site to the SC, through industrialisation and off-site production, and (4) integrated management of both the construction site and the SC. There still seems to exist a lot of discussion as to the applicability and usefulness of SCM in construction (Green et al., 2005; Fernie & Tennant, 2013). In a sense-making effort, Green et al. (2005) conclude that in contrast to aerospace industry, where SCM is an "imperative of global competition," in construction, SCM is only applied for operational improvement with "little evidence of strategic perspective." On the other hand, Van de Rijt et al. (2010) have already provided proof of a shift in construction towards performance evaluation and particularly not only cost-based but also quality-based. Additionally, Gosling et al. (2015) performed a longitudinal study of the impact of SCM on performance metrics and concluded that the higher – or more strategic – the level of partnership is, the more consistent the performance indicators are. Therefore, it is inferred that the applicability and usefulness of SCM closely depend on the strategic goals of the various SC networks that adopt it.

§ 2.2.3 Integration of the Supply Chain

The concept of integration in SC research is again a concept appropriated from the manufacturing SC research (Dulaimi et al., 2002). In this context, integration is typified by two distinct strategies: horizontal and vertical integration. Horizontal integration refers to the incorporation of similar parts of the production chain, to control the competition, while vertical integration refers to the internalisation of dissimilar and complementary upstream and downstream firms along the SC, to control the uncertainty (Vrijhoef, 2011). Although the concept of vertical integration seems quite more related to SCM, it is not identical to SCM, as the former implies ownership of the upstream and downstream activities (Christopher, 2011). After all, integration in the SC involves the incorporation of activities and not of firms; that could carry additional contractual and legal implications.

Integration is, literally, the opposite of differentiation, and to some, it implies hindering financial flexibility (Fernie & Tennant, 2013). However, in the construction industry the motives are not only financial, given that integration aims to minimise the interfaces between either the SC and the site or among the various SC actors and, therefore, improve the dependability of the activities (Vrijhoef & Koskela, 2000). Integration is considered the antidote to fragmentation. Whereas SCM focuses on the regulation, re-channelling, and management of the various flows in the supply chain, SC integration takes the management goal one step further. Integration in the SC context is attributed to a "higher level" of management as to the combination of shared information flows or joint activities and operations (Vrijhoef, 2011). In the context of this thesis, SCM was considered a prerequisite for achieving integration. Thus, the concept of 'management' was used throughout the thesis, as opposed to the term 'integration', which is mostly used in the final chapters, from Chapter 5 onwards. Integration is seen as the end goal of close SC collaboration and successful SCM practices.

Supply Chain integration has been a preeminent concept in SCM research. The terms integrated SC or integration have already been used to describe a mature form or SCM (Lockamy III & McCormack, 2004). Eriksson (2015) takes another standpoint to analyse the SC integration in four dimensions as to the (1) strength, e.g. through a combination of selection and incentives parameters, (2) scope, (3) duration and (4) depth, e.g. how many tiers are involved in the integration. However, this approach is quite descriptive, as it focuses more on the attitudes and the intentions, rather than the actual activities that could deliver integration (Eriksson, 2015). This thesis used some of these descriptive qualities to define the maturity of the supply chains and rationalise the case study selection process in Chapter 3.

To further define, analyse, and evaluate the degree of integration in SCM, Vrijhoef (2011) defines and examines the concept of integration as to a set of goals that are further assessed by a set of factors. Vrijhoef (2011) concludes with ten goals for Supply Chain integration clustered around the areas of (1) productivity or improved flow of production, (2) market position or improved commercial success, (3) product or enhanced total quality and (4) team performance or improved collectivism and image. These goals, which define SC integration, are supported by eleven factors that are accordingly clustered to the areas of (a) integration (of operations, information, and logistics), (b) market development, (c) collaboration and (d) quality management (Vrijhoef, 2011). Table 4 associates the factors with the overarching goals of SC integration (Vrijhoef, 2011, p. 225). The thesis used these afore-mentioned factors during the analysis of SC management practices in Chapter 3.

TABLE 4 Main goals for SC integration and the associated factors, or activities to attain them. Adapted from Vrijhoef (2011:225).

	FACTORS	GOALS			
		Productivity	Market position	Product (quality)	Team performance
A	Repetitiveness	x	-	x	-
	Integration of operations and processes	x	-	-	-
	Information exchange	x	x	-	-
	Planning and logistics control	x	-	-	-
B	Product design and development	-	x	x	-
	Integration of business activities	-	x	-	-
	Market approach and marketing	x	x	-	-
C	Partners sourcing & collaboration strategies	x	x	-	x
	Human resource management	x	-	-	x
	Cultural alignment	-	-	-	x
D	Quality management	-	-	x	-

§ 2.3 Pragmatic impact of Supply Chain thinking in AEC

§ 2.3.1 Supply Chain thinking Schools

From the above review on SCM and Supply Chain integration in construction, both qualitative aspects, e.g. strategy and collaboration, and quantitative, e.g. performance-related or Input/Output (I/O) approach, goals are considered. These 'qualitative' and 'quantitative' notions indicate that there exist two antithetical yet complementary fields pertinent to SC research. These antithetical notions resonate with the school of thoughts in Project Management: one more task-oriented and the other more organisational-oriented (Andersen, 2016). After all, Söderlund (2004) had previously argued that Project Management has one root in engineering and the other in social sciences. These could be further related to the shift that took place after the 1950s from the positivist to the non-positivist paradigm and their aftereffects. London and Kenley (2001) identify two main Supply Chain thinking research paradigms, one focusing on the I/O, which often "places boundaries around the project environment." The combination of these two approaches should be seen more as complementary, rather than antagonising. After all, the focus on strategic inter-firm relations, beyond strict project boundaries, could lead to increased performance, according to Gosling et al. (2015). Potentially the latter could induce the former as well, given that improved performance could be regarded as a prerequisite for the fostering and retaining more strategic relations.

Apart from the philosophical paradigm, the different national business cultures may contribute to the various interpretations of SCM in construction. Winch (2002, p. 24) distinguishes three basic types of advanced economy business systems, derived from their respective national business systems. These advanced economy business systems types could also apply to the construction industry, as to the (a) Anglo-Saxon type, e.g. the USA and the UK, (b) Corporatist type, e.g. Germany and the Netherlands and (c) State-led systems, e.g. France and Japan (Winch, 2002, p. 24). From Winch's (2002, p. 24) categorisation, it is evident that in Europe there are various idiosyncratic market characteristics that could potentially influence approaches to construction management. After all, Dubois and Gadde (2002a) had already noted the paradox that for the same under-performing construction industry and depending on their particular theoretical foundations and background, various construction researchers "prescribe either more competition or more cooperation to increase the performance of the industry as a whole." Arguably, apart from the various interpretations of the problems and the potential solutions, the concepts of SCM and integration per se might also present various nuances, depending on particular market characteristics.

SC thinking is a concept that was first transplanted from the manufacturing sector to the UK construction market after the *Rethinking Construction* movement initiated from the homonymous title of the *Egan Report*. The report suggested that pursuing "long term relationships or alliances" and "partnering the supply chain" would then deliver "sustained improvement" and value for the customer (Egan, 1998). Researchers on SC thinking in the UK construction industry are quite critical regarding its value and applicability. They consider that SCM hinders competition, and it implies unilateral control from one focal firm and inflexibility to the rest firms (Cox & Ireland, 2002; Briscoe & Dainty, 2005; Green et al., 2005; Fernie & Tennant, 2013). A potential explanation of this position is the inherent liberal market values in the UK, as echoes of the *laissez-faire* ideas and the existing "relative low levels of state regulation" (Winch, 2002, p. 24). As far as the UK industry is concerned, SC thinking in construction has been a long-lived concept. Despite the criticism from the UK, the SC concept has been transplanted to numerous other countries, as demonstrated next.

The USA has seen a partial democratisation of the SC concept. SCM has been applied mostly in the USA in the context of Engineering, Procurement, and Construction (EPC) projects. Australia is another Anglo-Saxon country where the SC thinking has also been adopted with a focus on inter-firm relationships. In Australia though, SC thinking is usually embodied in the format of alliances, rather than partnerships, because to them alliances imply a tighter contractual mechanism to share risks and rewards[2]. In the Netherlands, whose market characteristics have been previously analysed in the "Regional relevance" section, the inherent "risk aversion" of the industry (Dorée, 2004) is fertile ground for integrated partnerships. Surprisingly, no 'escalation of commitment' effects have been observed regarding the integrated partnerships (Rutten, Dorée, & Halman, 2014). Finally, in the Scandinavian countries, SC thinking has been adopted as a both I/O approach and simultaneously focusing on inter-firm relations, with an emphasis on the procurement aspect of construction activities[2]. The advantages offered by integrating the information flows through SCM could potentially increase the popularisation of the SC concepts globally.

§ 2.3.2 Supply Chain concepts and varying interpretations

Although SCM is a well-known concept that is adopted and popularised across many industries, it does not have a universal definition. Whereas this thesis has held a network or inter-organisational approach to SCM, still multiple concepts are valid. For Naslund and Williamson (2010) the lack of definitions contributes to a vicious circle of poor definitions and lack of empirical evidence supporting the benefits of SCM. Among the most popular concepts and source of misconceptions, is when referring to Supply Chain either as the whole industry or the firms that participate in one single project. This idea appears mostly in the construction industry and particularly in the literature of the UK and could be responsible for the disbelief that surrounds the discussion of the benefits of SCM (Fernie & Tennant, 2013). To categorise the research on construction SC, Vrijhoef and London (2009) distinguish intra-organisational, inter-organisational and cross-organisational levels of analysis. The remaining various concepts and definitions have been related not only to SCM but also to the type of the Supply Chain under study.

2 Based on anecdotal information from Australia- and Scandinavia-based researchers and practitioners.

Usually, SCM is considered synonymous with the existence of contractual arrangements among the involved firms, i.e. partnering. Fernie and Tennant (2013) in their effort for a definition of SCM, based on grounded theory, detected that often SCM and partnering philosophy are used interchangeably in the scientific literature. Other supply chain researchers refer to supply chain partnerships (Briscoe, Dainty, & Millett, 2001) or supply chain partnering (Venselaar, Gruis, & Verhoeven, 2015), or simply partnering (Eriksson, 2015). Partnering is a quite more general term, given that it describes the contractual and other activities but not the end goal of the relationships among the various involved firms. For example, the term partnering might describe open-ended (strategic) or fixed-term agreements. Partnering entails either *project-specific* or *long-term* goals in *temporary* or *permanent networks* of firms respectively (Dubois & Gadde, 2002a; Gadde & Dubois, 2010). In general, partnering could be perceived as a pre-requisite for SCM, given that the inter-firm relations might require a definition before being managed. In this thesis, the two terms were usually combined, i.e. in the term 'Supply Chain partnership', so as to differentiate among the whole project supply chain and a contractually-bound fragment under study.

The term 'Supply Chain' is also used to describe a generic smaller part of the industry, as to the type or size of the involved firms, their building expertise, e.g. prefabricated housing, timber construction or companies that collaborate on the delivery of a particular material, e.g. in pre-cast or concrete reinforcement chains (Aram, Eastman, & Sacks, 2013). Another type of 'Supply Chain' is the differentiation between 'backward' and 'forward' chains, which are also typically referred to as contractor-led (or supply-led) and client-led (or demand-led) supply chains respectively, where demand could also play a role in integration (Briscoe, Dainty, Millett, & Neale, 2004; Briscoe & Dainty, 2005). Again, the clients, being larger organisations, often do not share the same strategic goals with the contractors and that could explain the lack of integration on the demand side of the construction SC (Briscoe & Dainty, 2005). These smaller or larger fragments of the industry do not necessarily share the same strategic goals, apart from the same functional expertise, and therefore, this fragmentation could be another source of misconceptions.

This section aimed at explaining how SCM has been perceived and interpreted in the context of this thesis and not at providing the absolute definition of SCM. The aim was to support and potentially add to the debate about the benefits of SCM and contribute to its rationalisation and popularisation. As mentioned in the "Regional relevance" section, the case studies upon which this thesis is based were all located in the Netherlands. In the Dutch construction industry, the concept of SC is often referred to as *keten*, whose literal translation is *chain*. The terms *ketenbeheer*, *ketensamenwerking*, and *ketenpartnerschap*, are used interchangeably and mean Supply Chain Management, Supply Chain Collaboration, and Supply Chain partnership respectively. To ensure that the same concepts were used by both the researcher and the case participants, the existence of a contract was considered a prerequisite for defining the SC partnership, through the use of SC contracts or framework agreements. Therefore, the SC framework agreements were devised as an identifier of the SC partnership, which could demonstrate an explicit agreement among the SC actors, and a rudimentary level of defined or linked SCM maturity (Lockamy III & McCormack, 2004). Whereas an interpretivist approach was undertaken as to recognising the different perspectives of the various actors, a slightly more normative approach was used to describe the phenomenon of the SC partnership and connect it with similar phenomena. Numerous researchers have been studying the concept of SCM in the context of SC partnerships, i.e. dyadic relations between firms (Lambert, Emmelhainz, & Gardner, 1996; Mentzer, Min, & Zacharia, 2000; Mentzer et al., 2001). In this research, as the research focus is at an industry, i.e. AEC, level and multiple disciplines are involved in the project delivery, the term 'SC partnership' denotes multiple 'dyadic' relations, usually stemming from the contractor towards various multi-disciplinary actors of the AEC SC. Figure 5 illustrates the afore-described concepts and the third diagram from the left is a schematic representation of the SC partnerships on which this thesis has focused, i.e. a network of inter-connected firms across multiple tiers. In this thesis, a SC is considered a network of firms engaged in long-term partnering relations and observed in 'snapshots' or cross-sectional studies of their projects.

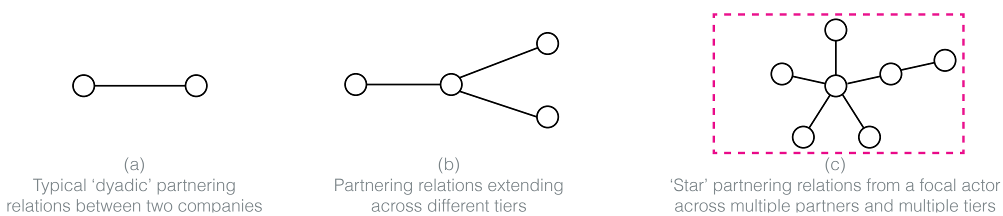

FIGURE 5 Different types of SC partnerships: (a) dyadic, (b) across tiers, (c) multiple dyadic across tiers from a focal actor.

§ 2.4 Origins and development of Building Information Modelling

§ 2.4.1 From Building Product Models to BIM

Thinking in products, rather than processes, has been considered a paradigm shift for the construction industry. Apart from the need for rationalisation and normalisation of processual aspects of construction, analogous efforts have taken place in the area of product-related research. During the 1970s and mid80s, one of the most predominant line of though was dealing with the problem of structuring information so as to represent knowledge about facts and artefacts (Eastman, 1999, p. 111). This shift naturally followed similar changes in other industries, such as again, the manufacturing and aerospace industries. With initiative from the USA Air Force, product definitions were developed around the mid-80s to support "the direct and complete exchange or sharing of a product model amongst computer applications, without human intervention" (Dado, Beheshti, & van de Ruitenbeek, 2010). These efforts, which coincided with the first efforts for standardisation, aimed at replacing the existing product definitions that were based on graphics and two-dimensional (2D) geometry and were prone to misconceptions and numerous different interpretations from the human agency.

The advancements in product modelling from other industries joined the long-standing debate on the computerisation of AEC (Eastman, 1999, p. 30). Dado et al. (2010) define a product model as an integrated representation of information and data about an act over its product life-cycle. In the context of AEC industry, the term Building Product Model (BPM) is used to denote the information about a building component embedded in a product model (Eastman, 1999). Nederveen et al. (2010) differentiate BPM from older technologies as to the potential of the former to be stored explicitly in a formal, computer-interpretable manner, without been susceptible to human interpretation. The origins of BIM are found in various approaches for object-oriented building product modelling that took place in the 1990s (Eastman et al., 2008, p. 354). Essentially BIM authoring applications follow the principles of Object-Oriented Modelling. A massive uptake of BIM appeared in the last decade, although it has been considered an unfulfilled prophecy for more than three decades. During this period, various standards have been developed, eagerly supported, and discontinued.

Whereas currently, the terms Building Information Modelling and, its acronym, BIM have been made synonymous with various commercial software solutions for AEC, BIM is essentially an 'umbrella' term, similarly to the SCM philosophy. This umbrella term denotes apart from its merely commercial instances, e.g. software applications such as Autodesk Revit, Bentley Microstation, Graphisoft Archicad and numerous more, the process of modelling building products, also known as 'BIM-ing', the BIM-based processes in Design and Construction, as well as the outcome of these processes, i.e. the Building Information Model. This sub-section has provided a historical review on BIM from the product modelling efforts in AEC. To understand the future directions that BIM-related research will address in the coming years, a review of its core goals and attributes was performed next.

§ 2.4.2 Exchange and collaboration standards pertinent to BIM

Information exchange standards in AEC

A standard in IT is a set of solutions that aims at satisfying and balancing the needs and requirements from a diverse group of actors in a seamless manner for electronic communication within and between computers (Laakso & Kiviniemi, 2012). The standards are expected to be used “during a certain period, by a substantial number of the parties for whom they are meant” (Vries, 2005). Various efforts took place aiming at creating a standardised model for building product information in construction. The efforts for the standardisation of building information could be considered a form of “horizontal standard,” focusing on achieving compatibility among an array of building product entities (Vries, 2005). While it was beyond the scope of this thesis to offer a comprehensive presentation of all the developed standards pertinent to BIM, only a few seminal and highly relevant to the current and future research directions of BIM have been reviewed. This review of standards underlines their affinity to BIM and the role it could potentially play in the combination of SCM and BIM concepts, as they reappear in the subsequent thesis’ chapters.

The human-derived need to trust the exchanged information as to accuracy and conciseness, and the machine-based necessity for interoperability, motivated the efforts for standardisation. Those were organised from industrial consortia and cross-organisational bodies and began in the 1970s (Björk & Laakso, 2010). The Standard for the Exchange of Products model data (STEP) was the first effort in the AEC industry to combine human-readable graphical information to machine-readable information organised in Entity-Relation (ER) descriptions (Laakso & Kiviniemi, 2012). So far, the Industry Foundation Classes (IFC) standard, which was based on STEP, has been the most long-lived (Björk & Laakso, 2010). The IFC was specified and developed by the international non-profit consortium International Alliance for Interoperability (IAI). IAI is now named BuildingSMART and primarily focuses on standardising the processes, workflows, and procedures for BIM (BuildingSMART, 2014). Thus, the efforts for standardising product modelling information in AEC now shift towards standardising BIM.

IFC is a common language used for transferring concise information among various BIM applications. IFC has so far undergone various revisions, since 1994 (Laakso & Kiviniemi, 2012). The IFC has so far experienced four major versions and a couple of additions (Amor, 2015). Its strategic goals remain unchanged: to represent a neutral and open specification for BIM. Being neutral, suggests that it was destined to be a higher-level data model, above software implementations (Laakso & Kiviniemi, 2012). Being open, suggests that it aims at being exchanged and shared among the various AEC actors beyond system’s dependencies. Thus, it could allow and enable the various actors to customise their Information System (IS) infrastructure, still maintaining information transparency when collaborating with their partners. Therefore, the goals of standardising IFC- and, therefore, BIM – are aligned with the ideas of managing the information flows in SCM practices among various SC actors.

In practice, IFC presents still some drawbacks. The disadvantages stem from the inherent properties and development of the standard, but also from the actual process of building information exchange. The various versions of IFC have managed to deal effectively with the complexity of its schema, but often this creates semantic implications (Amor, 2015). In other words, IFC could be still described as an ambiguous "weak- (or loosely) typed system" that allows for multiple interpretations of the objects (Venugopal, Eastman, Sacks, & Teizer, 2012). Therefore, focused considerations on semantics could potentially improve the consistency of the information exchanges through IFC (Amor, 2015). After all, Dado et al. (2010) have long awaited the future trends of building product modelling efforts to be found in the emerging Semantic Web standards such as Web Ontology Language (OWL) and Resource Description Framework (RDF) that are based on the concepts of ontology modelling. Towards these directions, also the efforts to define the IFC-based ontologies in both syntactic and semantic levels are found. For example, Beetz et al. (2009; 2014) and Pauwels et al. (2011) have proposed solutions for translating the IFC standard into OWL language (IfcOWL). All these approaches have the ultimate goal to increase the systems' interoperability and the semantic adaptation of the IFC so as to integrate further the AEC lifecycle and particularly the Construction and Operation phases.

The IFC is not the native model of the various BIM applications. Subsequently, some loss of information often takes place when the actors exchange IFC files that are converted from the proprietary formats. From a holistic inter-organisational – or SC thinking – viewpoint, the IFC promises quite consistent information among the various actors, despite these losses. Practical experiments of data exchange via IFC in the Netherlands have shown that the IFC standard continues to gain popularity among design and engineering teams (Berlo et al. 2012; 2015). An ideal future scenario, to minimise or eliminate the loss of information from one software platform to another, would be when all BIM-related software companies used more compatible native files, but this remains improbable due to the competition of the various software vendors. The IFC remain fairly promising regarding interoperability among the various native files that are used by the multi-disciplinary actors in a project. Given that longevity of the IFC standard is among the key goals of BuildingSMART, its continuous adoption could potentially also support a greater industrialisation of the AEC industry, given that when comparing AEC to the manufacturing sector, the former lacks the penetration of object-oriented product modelling approaches.

Collaboration standards in AEC

Another category of standards pertinent to BIM could be considered the various collaboration standards that emerge and aim at describing the function of BIM implementation, a type of vertical standard (Vries, 2005). For example, Constructive Objects and the Integration of Systems (COINS), which is also affiliated with BuildingSMART, is an effort since 2003, initiated in the Netherlands. It contains both exchanging formats and prescriptions of collaboration methods or principles of information management (Dado et al., 2010). COINS aims at offering complementary support to the implementation of BIM standards, such as IFC. Further review and analysis of collaboration standards for BIM, fall beyond the scope of this thesis, given that it aimed at investigating the transformations of processes, products, and organisations from the use of BIM and not to primarily focus on standards. Nevertheless, standardisation brings the industry a step closer to integration.

In the UK, a PAS (Publicly Available Specification) about BIM collaboration has been developed and revised since 2013. The British Standards Institution (BSI), which issues these PAS, is sponsored by the Construction Industry Council (CIC) and addressed to the various multi-disciplinary organisations of AEC. The PAS suggests a standardised manner to implement a new technology or guidelines and to serve a specific market need. The PAS 1192 consists of many updated specifications over the years. They are usually developed in collaboration with a consortium or other private organisation and are considered a precursor of standardisation. Regarding BIM, the PAS 1192 are considered guidelines to achieve the coveted, yet ambiguous 'Level 2' of BIM implementation on all public sector asset procurement by 2016. Like the IFC standard, the PAS 1192 is based on older collaboration requirements in the version of 2007. The PAS 1192-2:2013 specifies information management for the delivery phase of construction projects using BIM. The PAS 1192-3:2014 focuses on the operational phase of assets and offers guidance on the use and maintenance of the Asset Information Model (AIM). It intends to prescribe the collaboration process in BIM-based projects and information management to the various multi-disciplinary actors. Previously, some UK-based researchers have opposed to top-down approaches to BIM and suggested that bottom-up BIM implementation approaches could overcome the resistance to change on behalf of the participating firms, by utilising both the employee's potential as well as conscious change management strategies (Arayici et al., 2011). It seems that whereas the concept of BIM becomes increasingly relevant, the exact process to implement it is still quite ambiguous, and requires further external and top-down regulation in the UK.

Other specifications of Building Information

Construction Operations Building information exchange (COBie) is a set of data specifications, which includes a data schema and data capturing process. COBie was introduced to illustrate how information from the IFCs could be provided from the designers to the Facility Management (FM) (East, 2007). Subsequently, this specification, which is essentially a spreadsheet translation of the IFC, provides insights into the actors that model the information in the associated lifecycle phases. Also, this specification presents building information in a non-graphical yet highly intuitive and accessible human-readable manner. It this context, COBie could also be viewed as an "operational standard" (Yalcinkaya & Singh, 2015). COBie is similar to a 'birth certificate' of building information and aims to be used during the later stages of the projects for operation or maintenance. The review of COBie was not further continued in this thesis, because, unfortunately, COBie contains information about the generation and not the sharing and exchanging of information, which has been the focus of this study. However, COBie after some usability enhancement could reveal a promising way forward as to the management of Building Information beyond Design and Construction phases, as it is avidly promoted by the PAS specifications in the UK.

§ 2.5 Opportunities for SCM from BIM applications

§ 2.5.1 The adoption of ICT capabilities in AEC

With the advent of technology, solutions from Information and Communication Technology (ICT) are becoming increasingly popular for the management of construction projects. Given that ICT offers tools for making informed decisions, it could manage the project complexity. This thesis reviewed such applications as to their usability for management. The ICT approaches offer informational and analytical tools for assisting the involved actors in a variety of Design and Construction processes, by allowing the access and sharing of information. Among the first application areas of ICT in construction were the graphical and visualisation capabilities, e.g. from Computer-Aided Architectural Design (CAAD), data analysis, information sharing, communication, and collaboration, via numerous Internet capabilities. BIM has been considered such a new type of ICT – or better simply IT, as it generally lacks communication capabilities –, with built-in features of generating and managing building information, e.g. three-dimensional (3D) design, visualisation, automated drawings and codes generation, and quantity take-off.

Construction ICT has focused either on design or management capabilities (Forbes & Ahmed, 2010). For example, past solutions that used ICT for management in AEC focused primarily on exchanging information so as to manage the invoices, quantities, and crews. For communication, most organisations used extranets (Ajam, Alshawi, & Mezher, 2010), ERP, and online project databases for information management. Through these massive IS the actors exchange and share various project documents, such as planning in the form of Electronic Document Management (EDM), orders and invoices in the form of Electronic Data Interchange (EDI) and less often building information, either as printed documents, from CAAD applications or as object-oriented models, e.g. BIM. However, so far no technology has been globally accepted from all the various AEC disciplines both at a document type of the exchanged information or the type of used IS (Samuelson & Björk, 2013; Demian & Walters, 2014; Samuelson & Björk, 2014). Overall, object-oriented, e.g. BIM-based, models have rarely been adopted in the past (Demian & Walters, 2014). BIM offers capabilities for combining both design and management capabilities and thus is inclusive and intuitive.

A variety of IT applications for design and management could be supported by BIM, either from the built-in features of the BIM authoring software or by specialised or customised tools. Cao et al. (2014) categorise the various BIM applications as to the respective phases that are used: design or construction phase. The framework of Cao et al. (2014) has been heavily influenced by Gao and Fischer's (2008) framework, which categorised the various BIM applications as to visualisation, coordination, and collision detection or avoidance. However, to further analyse the impact of these applications, this study classified BIM applications as to the scope, i.e. their relevant management area. BIM as an IT could support four areas of management in AEC projects: design management, information management, construction management, and performance management:

- *Design management* includes the notions of initiation and project scope (and also any considerations for sustainability) and ensuring collaboration among the project team.
- *Information management* category includes the BIM-based efforts of data and interoperability as well as the need to distribute consistent information to the various multi-disciplinary project actors.
- The aspect of *construction management* includes all efforts for managing the construction site and maintaining the facility, such as construction site management or FM.
- *Performance management* entails management considerations that additionally focus on special isolated performance metrics, not applicable to all projects.

From the above categories of BIM's capabilities for the management of AEC, this thesis further emphasised on design, information, and construction management. Given that the overarching research goals relate to the further promotion of SCM in

AEC, no extraordinary building performance considerations were taken into account. At the same time, design and construction management refer more to the material flows of the SC concept, whereas information management relates to the intangible information flows of AEC projects. The capacity and potential of BIM to management these tangible and intangible SC flows were reviewed next.

§ 2.5.2 The potential of BIM in support of the SC flows

Material flows

BIM, being a building product model per se, could support the material, or building product flows during the Design and Construction phases of AEC. During the Design phases, BIM offers various capabilities for updatable and consistent quality management and quantity take-off calculations of the materials to be used in a project (Eastman et al., 2008). The material capabilities of BIM start from the potential for quality management, by comparing and ensuring the compliance of the selected material to the project specification requirements and the construction codes (Chen & Luo, 2014). The object-oriented logic behind BIM could not only automatically produce the Bills of Quantities for the project, but also dynamically enrich it with model properties (Eastman et al., 2008). Therefore, BIM could support the material flows, even before they are procured and placed on the site. This possibility of BIM could play the role of transferring the site activities to the SC, as described by Vrijhoef and Koskela (2000). Subsequently, the preparatory activities on the site have the potential to start before the actual delivery of materials.

During the Construction phase, the object-oriented capabilities of BIM could be used to support various site activities, such as the transportation of the materials, their distribution on site and the optimisation of the construction site layout. BIM combined with the use of mobile technologies could develop and maintain feedback mechanisms between the design and construction teams (Irizarry, Karan, & Jalaei, 2013). Simultaneously, BIM could monitor the supply chains by integrating tracking technologies, such as barcodes, RFID, and Global Positioning System (GPS), to enhance the visibility during the material delivery (Irizarry et al., 2013). Other BIM applications for the material flows concern the control and optimisation of the construction site layout, by linking BIM to algorithms for automated site storage planning (Kumar & Cheng, 2015). Concerning the flow of equipment on sites, coupling BIM and GIS technologies, could support the decision-making process for the layout of construction equipment on site (Irizarry & Karan, 2012). Therefore, technologies such as mobile, GIS and RFID could be combined with BIM to regulate and optimise the material-related flows of the SC and contribute to SCM applications such as integrated operations, logistics control (Vrijhoef, 2011). Ergo, BIM has the potential to act as a multi-faceted integrator of various technologies and processes for the monitoring and the control of material flows in the construction site.

The material flows are considered a downstream flow of the digital and physical materials on the construction site. At the same time, there is a highly associated flow to that, which concerns the cash flows of the materials. BIM is used for calculating the cash flows after automatically extracting the Bill of Quantities and strengthening the feasibility and control of project cost analyses. After all, the project benefits of BIM include cost reduction, given that enhanced control and time savings could be observed by applying BIM to these processes, according to Bryde et al. (2013). Forgues et al. (2012) claim that the cost estimating methods have changed enormously after the introduction of BIM, primarily due to the accompanying organisational changes that BIM entails. However, the BIM-based cost estimating processes cannot yet completely replace the traditional methods as Hartmann et al. (2012) point out. The reasons for that might be found in the remaining barriers to the full potential of BIM for quantity surveying, given that the quality of information in BIM currently requires additional checks for its accuracy (Aibinu & Venkatesh, 2014). Thus, BIM apart from being a structured tool for controlling the material flows could sufficiently manage the cash flows of the AEC SC but needs some fine-tuning before being fully capable of supporting SCM.

This potential of BIM for managing the material flows of the construction industry aligns with the approach of Stanford Centre for Integrated Facility Engineering (CIFE), which is an academic and education centre for Virtual Design and Construction (VDC) in AEC. Virtual Design and Construction (VDC) uses multi-disciplinary computer models and applications, such as BIM, and aims at improving project performance by generating and managing 3D/(four-dimensional)4D modelling guidelines and implementations (Gao & Fischer, 2008). However, the objectives and approaches of CIFE for leveraging from BIM in construction focus on optimising the material flows and project performance, but do not focus on the inter-organisational relations. Therefore, as this thesis focuses on SC partnerships, further review of the efforts developed in CIFE will not be included.

Information flows

By definition, BIM facilitates and regulates the information flows about the building product. It offers methods for product modelling, interoperability, and distribution of project information among the extended project team. BIM ensures consistent product information via standardised solutions, as explained in sub-section § 2.4.2. Likewise, it offers options for collaboration via online platforms and improves the traditional data management. This investigation has been of particular interest in the case of SC partnerships, given that the uninterrupted information flow among the various actors is a factor towards greater integration of the SC (Vrijhoef, 2011). The potential of BIM to support the (content of the) SC material flows has been explained in the previous sub-section. This sub-section focuses on the information flows as to the interactions and collaboration among the actors and the process of their information exchange.

Various multi-disciplinary actors use BIM and particularly information exchange via IFCs to share information with their project collaborators. Usually, this aspect of information exchange is wrongly mistaken for interoperability. Interoperability refers to a machine property and particularly to the ability of the various ICT systems or software applications to exchange data and use the information consistently. Given that BIM is a relatively new technology, some interoperability issues remain at syntactic and semantic levels, despite all the standardisation efforts (Lee, Eastman, & Lee, 2015). For example, in a comparison among the interoperability of three software from leading vendors in BIM applications (Autodesk, Nemetschek and Graphisoft), based on the second version of IFC, proved to be dissatisfying as to the necessary manual effort that had to accompany the information exchange among the various users (Pazlar & Turk, 2008). Therefore, BIM requires special efforts on behalf of the various multi-disciplinary actors to ascertain that the exchanged data are accurate, consistent and usable from their collaborating partners (Owen et al., 2010). Besides interoperability, others advocate that the complexity of the BIM-based information flows has not been merely an ICT issue, but a "richer interweaving (set) of processes, culture and values, and management of contractual issues" among the stakeholders (Grilo & Jardim-Goncalves, 2010). Accordingly, this study has focused more on the interaction among the various SC actors and their actual collaboration process, rather than the properties and the interoperability of the IS that they use.

The new emerging patterns of interactions among the various project participants gradually suggest a self-organising network of information flows. Sebastian (2011b) claims that BIM adoption has caused changes not only in the products and processes but also in the roles of the contractors, architects, and clients. The project team has been enlarged with all sorts of consultants and specialists and some parties that used to play a secondary role in the traditional procurement process, but now play a more active role in design and construction, such as project managers, energy consultants, property developers, and facility managers. For example, the clients and property developers have been playing a dominant role as to the demand for including BIM in project delivery (Porwal & Hewage, 2013). After all, several public sector initiatives from Denmark, Finland, Norway, and the Netherlands have promoted BIM-based collaboration during projects and particularly using openly available standards (Laakso & Kiviniemi, 2012) for years. Likewise, the contractors have been looking at BIM as an especially leveraging activity and especially as to SCM (McGraw-Hill, 2014). Given that more and more disciplines adopt BIM-based tools and technologies, the changes among the SC actors are highly dynamic. The capacity of BIM, as prescribed in the sub-section § 2.4.1, could provide multi-disciplinary options throughout the project life cycle. Nevertheless, the exact impact of BIM on the information flows, and these new emerging roles have not defined yet and the project teams – strategically integrated or not –adopt the new technology without making the appropriate managerial shifts.

These various newly emerging roles pertinent to BIM are caused not only by the introduction of this continuously developing technology, i.e. BIM, per se but also from the multiple tools offered by BIM software. So far, there no comprehensive software suite exist to capture the needs and functionalities of the multi-disciplinary project actors of AEC (Eastman et al., 2008). Whereas there is a common misconception that BIM could offer a centrally – even real-time – capability for sharing and exchanging building product information, in fact, the BIM-based design process is far from central. The BIM-based collaboration could be concurrent only in homogeneous environments, e.g. with native file shared on the network, on a remote database, or on a BIM server (Cerovsek, 2011). Also, Berlo et al. (2012) have disproved the central arguments for BIM-based collaboration, and propose workarounds that offer acceptable BIM interoperability among a network of numerous multi-disciplinary actors. Namely, the collaboration through BIM could be supported by 'reference (or aspect) models' is a satisfactory manner (Berlo et al. 2012; 2015). Therefore, the information flows of the involved actors develop in non-central, potentially asymmetric and asynchronous configurations. Hence, the information flow, a core aspect of SCM, despite being sufficiently supported by BIM as to content, may occur in numerous possible collaboration patterns.

The above asymmetrical, imbalanced, and asynchronous BIM collaboration patterns that emerge from the BIM-based information flows are also present in strategic (or not) partnerships or projects. It is assumed that in more strategic relations among the involved actors, which rely on contractual, collaborative, and performance measurement agreements, the consistency of project results is higher (Gosling et al., 2015). When no SCM practices are applied, the temporary and limited character of the project-based organisations that lack strategic vision and alignment does not allow for the full adoption of all relevant possibilities for information management. Subsequently, such a lack of trust at an inter-organisational level undermines the quality of the information exchanges (Adriaanse, Voordijk, & Dewulf, 2010a). Simultaneously, IFC, the almost globally accepted BIM-standard, is associated with issues of trust on behalf of the multi-disciplinary actors (Cerovsek, 2011). Therefore, apart from the need to trust the project partners, there is need to trust the exchanged information, as to accuracy and conciseness. Whereas BIM-based collaboration – or model-based collaboration in general – could support the information flows, several challenges remain as to both technology-related and organisational aspects. BIM has not been proven efficient in managing the integration of business activities or the cultural alignment, which are applications that could further leverage integration from SCM (Vrijhoef, 2011). It becomes apparent, that whereas BIM could sufficiently manage the information flows, the remaining challenges of information exchange, transform the collaboration among the actors. Although the concept of BIM becomes increasingly popular, the exact process to implement it is still quite ambiguous, given that it is largely based on interoperability and specific software applications, which are developed and updated rapidly. In the future, BIM will probably consist of numerous interoperable packages or applications customised to the needs of the different disciplines. Thus, this PhD thesis supports that the implementation of BIM – or of any other aspiring digital means for generating, sharing, and managing building information – could stem from the individualities of the various multi-disciplinary actors and not from its technical features.

§ 2.6 BIM adoption and maturity

§ 2.6.1 BIM adoption and bottom-up implementation

The above review on how the information flows could self-organise in the era of BIM technologies, suggests that the concept of BIM is currently in flux. There exists research on real-worlds cases of BIM implementation as early as 2007 on various projects and also among multi-disciplinary teams (Ballesty, 2007; Sacks, Koskela, Dave, & Owen, 2009). Nearly a decade after the early attention that BIM received, its adoption is neither uniformly globally established, nor similarly functioning. Market reports such as from McGraw-Hill Construction (2009, 2012, 2014) underline preliminary positive outcomes of adopting BIM and further emphasise on the extent of BIM's diffusion. However, such commercially sponsored research could be interpreted as an indication and not as a proof of the status of BIM adoption, given that they usually focus on specific countries or actors, e.g. contractors. Concerning the other countries, BIM's diffusion in the Western Europe, Scandinavia, Australia, and South-East Asia is also advanced (Succar & Kassem, 2015). Despite that the term 'adoption' is mostly associated with a national level, but could also refer to industry consortia, organisations, professional bodies or even individual professionals.

The multi-disciplinary actors display varying adoption profiles for BIM technologies. According to the illustrious diagram produced by Rogers (1962) on the diffusion of innovations, the present adoption of BIM could be currently be placed somewhere between the tipping point among early adopters and early majority. Figure 6 illustrates the theory of the diffusion and adoption on innovations from Rogers (1962). At the moment, apart from the innovators in the field of BIM, there are many critics, pragmatists, and conservatives. Whereas Rogers' (1962) theory on how innovation travels through various channels over time, i.e. diffusion, originates from the 1960s, it is still very topical and applicable to different technologies or other contexts (Rogers, Medina, Rivera, & Wiley, 2005). However, other long-standing theories on technology frameworks almost contemporary to that of Rogers, such as the users' Technology Acceptance Model (TAM) by Davis (1989) cannot have the same resonance now. The reason could be potentially on the fact that the technologies currently linked to BIM have had a long history from as early as the mid80s (Eastman, 1999, p. 111). Thus, it would be unsuitable to analyse BIM adoption with TAM theory, given that BIM has built upon decades of gradual technology 'pull strategy' as explained in section § 2.4.

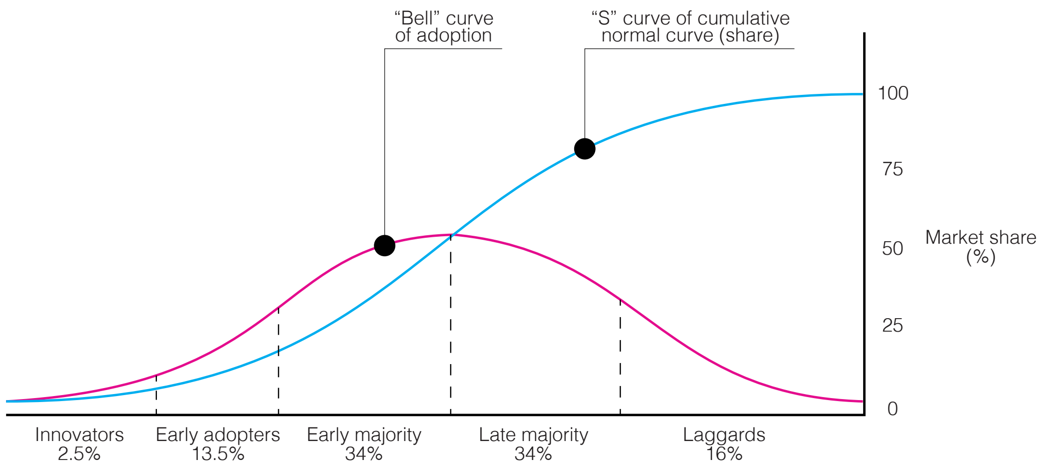

FIGURE 6 Rogers' (2010) theory on the adoption and diffusion of innovations.

Rogers (1962) describes five types of innovation adopters: the *innovators*, the *early adopters*, the *early majority*, the *late majority* and the *laggards*. These types make the 2.5%, 13.5%, 34%, 34% and 16% of the market share (Rogers, 1962) accordingly. At the moment, not all countries are at the same BIM adoption level. Froise and Shakantu (2014) claim that in the USA, the adoption of BIM has reached the late majority whereas in Europe it was at the early majority stage around 2010. After all, in the USA about 79% of the contractors declare that they have reached high or very high levels of BIM implementation (McGraw-Hill, 2014). However, as mentioned above, BIM adoption refers apart from countries also to individuals or organisations. Therefore, the BIM implementation from all these categories might be located in various stages. Succar and Kassem (2015) suggest that regardless the innovation attitude, similar BIM implementation stages apply. The adoption of BIM depends on three phases of BIM implementation: (a) readiness (or pre-implementation), which includes the preparation and the capacity of an organisation to innovate, (b) capability (or wilful implementation), which includes the set of interrelated technologies, processes and policies for the application of BIM, and (c) maturity (or post-implementation), which refers to the improved, repeatable, and predictable BIM implementation (Succar & Kassem, 2015). These stages have further been used in this thesis.

Regarding readiness, the again famous "MacLeamy curve", was created by Partick Mac Leamy to illustrate the advantages of IPD and BIM, but is also used to describe the bottom-up efforts for BIM implementation among the multi-disciplinary AEC firms as opposed to the traditional or CAAD-based process. The "MacLeamy curve" was based on Paulson's (1976) curve that associated the influence of decision-making on construction project costs. Figure 7 presents the popular *MacLeamy curve* and its associated concepts. Many other examples indicate the determination of the AEC firms to develop further their BIM capacity. Porwal and Hewage (2013) have discussed the emergence of new roles of "BIM managers" to control the BIM implementation in AEC projects willfully. At the same time, specialised BIM consultancies have been undertaking various BIM-based activities that traditionally were assigned in the architects', contractors' or quantity surveyors' organisations respectively (Aibinu, 2015). Finally, the empirical explorations of van Berlo et al. (2012; 2015) indicate repeatably and continuously improving efforts on behalf of various AEC firms to improve their BIM implementation process. Ad hoc and firm-centred approaches on BIM do not further promote the matureness of BIM implementation. This thesis suggests that by focusing on the adoption in already structured partnerships with some level of existing trust and beyond organisational barriers, i.e. SC partnerships, this process might potentially be smoothened and with a smaller learning curve.

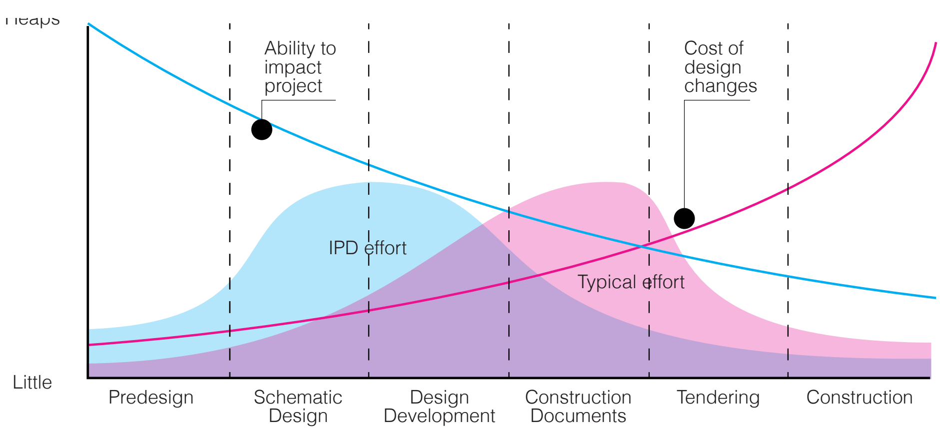

FIGURE 7 The "MacLeamy curve" prepared to illustrate the relation between the typical effort in traditional processes and the effort required by IPD. It is also used to illustrate the "BIM effort".

§ 2.6.2 BIM maturity frameworks and top-down strategies

The opposite of the afore-described bottom-up diffusion strategies are the top-down strategies. Eastman (1999, p. 30) described that in construction industry, the 'bottom-up' innovation diffusion has been the norm:

"innovations have been adopted that are both organisational – such as the recent development of fast-track scheduling – and also technical – such as the use of finite element modelling and the electronic storing and transmission of drawings. However, all the changes have been incremental, adopted first in pilot cases, then slowly absorbed into the wider practices of the industry as a whole".

Kassem et al. (2015) identified and analysed numerous publications from various governmental bodies, industry associations, communities of practice, and research institutions, which aim to increase awareness and support BIM adoption, in Australia, Denmark, Finland, the Netherlands, Norway, Singapore, UK, and the USA. They analysed noteworthy publications from those countries that were issued either as guides, protocols or mandates, as to the level of their information and compulsoriness, and further subdivided as to their form, e.g. reports, manuals, and contracts (Kassem et al., 2015). Edirisinghe and London (2015), analysed BIM standards and policy initiatives globally and concluded that there is an" influential link between national policy initiatives and the adoption data" from the practitioners.

Among USA, UK, and the Netherlands, whose BIM adoption is present in all studies above, USA has had the most advanced level of top-down BIM regulation and adoption. The USA has had a mandatory BIM use already since 2007. In the Netherlands, there exist downward suggestions and prescriptions since 2012. However, these suggestions are optional and at a higher level. Potentially a "wait and see" mentality towards innovation that previously applied to the Dutch contractors (Bremer & Kok, 2000), also applies to the Dutch government bodies responsible for the diffusion of BIM. Recently, Germany announced the mandatory BIM use in public projects from 2020 and a pilot use phase until 2017 (BMVI, 2015). In the UK, a mandatory mature level of BIM (Level 2) will commence in 2016, as prescribed in the relevant PAS.

The top-down strategies for BIM adoption in the UK are of particular interest, given that the UK market will subsequently undergo an intensive period of BIM adoption for the coming five years. Until 2014, the BIM engagement among more than half of contractors in the UK was low (Edirisinghe & London, 2015). Bew and Richards developed in 2008 a BIM maturity diagram and defined four maturity levels, where CAAD-based projects are at Level 0 and highly integrated and interoperable buildings data are considered of Level 3 (GCCG, 2011). The UK BIM maturity wedge and the related Levels are illustrated in Figure 8. According to this BIM maturity diagram, also known as ‘the wedge’, Level 1 concerns a primary 2D or 3D design. Level 2 BIM refers to a common environment where multi-disciplinary data would be shared using COBie. Level 3 BIM refers to the integrated and interoperable version of BIM, with a focus on using common dictionaries, IFCs, and common processes, with the aim to facilitate lifecycle management via BIM. By 2016, Level 2 BIM and the use of PAS 1192 will be mandatory for all public sector projects with a short adjustment period of four years.

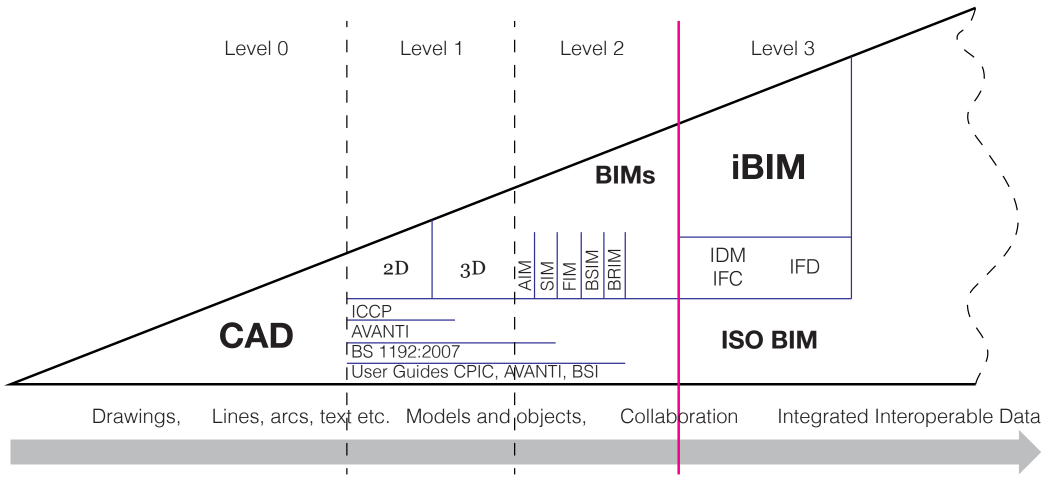

FIGURE 8 The UK BIM maturity wedge including the BIM Levels (GCCG, 2011).

§ 2.6.3 Mismatch between top-down and bottom-up implementation

Undoubtedly, from the previous two sections, BIM adoption appears to be in the spotlight of various public and private parties of AEC and different levels. However, challenges as to BIM adoption remain from both bottom-up and top-down strategies. On the one hand, market reports such as from McGraw-Hill Construction (2009, 2012, 2014) can capture only one fragment of the diffusion of BIM, and particularly from large contractors and not SMEs. These reports are probably not very relevant to Europe, given that, for example, the European construction sector is composed of around 99% of SMEs (UEAPME, 2015). On the other hand, the actual utilisation of BIM does not always evolve in practice as proclaimed, prescribed, and desired by the rigid top-down policy-making strategies. The mandatory downward implementation may disproportionately increase not only competition but also frustration. Moreover, the various adoption levels among countries imply a potential limitation as to the globalisation of construction, given that further differentiation of BIM implementation will contribute to the already diverse building regulations, metric standards, and building laws among countries. Therefore, there is a need for an integrated and global approach to BIM.

Market coordination problems have been previously identified regarding the need to standardise the file exchange formats (Laakso & Kiviniemi, 2012). Despite the efforts from the industry consortia, these efforts could only be considered successful after the catalytic intervention of the policy level. Succar and Kassem (2015) point out that normative diffusion policies for BIM within a particular market might trigger "through mimetic pressures" similar actions by other governmental and authoritative bodies in other countries. Subsequently, the diffusion dynamics indicate that many countries, following horizontal pressure mechanisms, could in the future adopt the mandates of other national policies, for example as to the PAS 1192. Apart from the bottom-up and top-down diffusion dynamics, also, the "middle-out" level could potentially play a role in strengthening the adoption of BIM (Succar & Kassem, 2015). Succar and Kassem (2015), claim that large organisations or industry associations could play a role as to influence (a) the smaller organisations coercively (downwards), (b) the governmental bodies normatively (upwards) and (c) the other large organisations mimetically (horizontal). Studies from the UK report that although many large contractors are UK BIM Level 2 (or even Level 3) capable, they face a difficulty to find equal BIM capability across the SC (Gledson & Greenwood, 2016). Considering SC partnerships as an intermediate level between national policies and isolated firms, they could potentially play a role in BIM diffusion also across less capable firms.

SCM and SC partnerships could likewise play a role in assisting the popularisation of BIM and at the same time invoke mimetic mechanisms as to popularise the concepts of partnering in AEC. After all, Winch (1998) while describing the dynamics of innovation – and considering BIM as an innovation –identified the top-down adoption dynamic as a stimulating superstructure and the bottom-up dynamic as a problem solving and learning activity. However, although the bottom-up approach involves the generation of new ideas and patterns through the problem-solving processes, the efficiency of this learning process and the applicability on future projects, greatly depends on the capacity of the firm (Winch, 1998). Thus, a mismatch emerges as to the appropriateness of the top-down strategies and the capacity of the bottom-up mechanisms for further and successfully diffusing BIM in AEC. The efforts to diffuse BIM from the 'middle-out' level also have the advantage of being detailed, similarly to the 'bottom-up' approach, and less high-level and not merely prescriptive than the 'top-down' policy's initiatives.

§ 2.7 Remaining gaps and potential solution

§ 2.7.1 Lack of analytic standpoints for Construction Research

The afore-mentioned mismatches as to the bottom-up and top-down approaches to BIM's diffusion also reveal an inter-organisational deficiency, i.e. complexity and fragmentation, of the AEC industry. Previously, the AEC has being characterised by a mix of loose and tight couplings between projects and firms from Dubois and Gadde (2002a). They further suggested that inter-firm cooperation and reciprocal adjustments of the involved firms would eventually foster learning and holistic improvement to both the construction product and the chains (Dubois & Gadde, 2002a). Mentzer et al. (2001) claimed that "SCM philosophy drives supply chain members to have a customer orientation." Whereas the benefits of the holistically managed collaborative supply chains to the clients are quite clear, i.e. improved construction product, the added value of collaborating cultures in construction is not self-evident (Fernie & Tennant, 2013). Moreover, the existing literature on SCM has repeatedly associated SCM with a lack of consideration for human agency and intra-organisational aspects (Green et al., 2005; Fernie & Thorpe, 2007). The multitude of participating organisations in a Supply Chain system suggests myriad relations that are difficult to trace and manage. The interweaving relationships of construction projects and firms cannot be analysed on a bilateral basis (Kornelius & Wamelink, 1998). Thus, there exists a lack of systematic analysis as regards SC thinking in AEC. O'Brien et al. (2002) have already proposed the combination of elements from operations management, analytic modelling, and industrial organisation theory to understand and interpret the ramifications of the construction SC.

Heretofore, research on the potential of SCM towards achieving integration has been studied by analysing various parts of the SC. For example, Vrijhoef (2011) analysed in detail the goals and the activities of distinct fragments of the SC in isolation, i.e. client, developer, designer, builder, and supplier, and later combined these findings and projected them to a comprehensive concept for SC integration. At a project level, Pryke (2009) has been analysing the various clients, consultants, contractors, and suppliers and their inter-relations for either knowledge transfer, information exchange or financial and contractual government, but without focusing on the process of their interactions respectively. Farshchi and Brown (2011) have used similar approaches to analyse the interactions and knowledge transfer among team members of construction projects. However, in the previous efforts, the involved actors and their collaboration (relations) have not been examined simultaneously.

Likewise, the research on BIM implementation lacks analytic approaches, and most research is one-sided from the perspective of individual actors. Winch (1998) claimed that for diffusing innovations – in this case, BIM – in the construction industry, the transition from the firm-oriented thinking to a network of firms thinking needs to be addressed. Few studies have analysed the interactions and the processes among the multi-disciplinary actors about BIM and particularly IPD (Hickethier, Tommelein, & Lostuvali, 2013). Also, most BIM-related studies have been focusing exclusively and separately on only the design team, client or the contractor, neglecting the subcontractors and the suppliers. Dubois and Gadde (2000) have highlighted that focusing also on the subcontractors, and the suppliers and including the supplier network could provide opportunities for 'joint learning' in construction projects. Thus, there is a lack of inclusive analyses of the inter-organisational relations and collaboration process of participants in BIM-based projects.

The two domains of SCM and BIM have been reviewed as opportunities for the AEC, in this thesis, and previously deemed compatible in section § 2.5.2, but both still lack in holistic approaches to dealing with the organisational complexities and fragmentation of AEC. Namely, the inter-organisational deficiencies of SCM and BIM have been explained in section § 2.3 and sub-section § 2.6.3. Thus, the gaps concerning SCM and BIM are found mostly in the capacity of their current practical and research directions to cope with and become relevant to all the multi-disciplinary participants of the AEC SC and particularly, to those with whom they are bound contractually.

§ 2.7.2 Thinking in Systems in AEC

From as early as the 1990s, the SCs have been described more as systems – or networks – rather than linear configurations (Christopher, 1992; Lambert et al., 1998). Mentzer et al. (2001) suggested that SCM as a management philosophy is closely affiliated to system considerations. They concluded that SCM implies a (a) necessary systems approach, which considers the SC as a whole and manages the "total flow of goods inventory from the supplier to the ultimate customer", (b) "strategic orientation towards cooperative efforts to synchronise and converge intra-firm and interfirm operational and strategic capabilities into a unified whole", and (c) "customer focus to create unique and individualised sources of customer value, leading to customer satisfaction" (Mentzer et al., 2001). Often, such system-based views for the SC, focus more on the inclusiveness of the multi-disciplinary actors, e.g. clients, customers and suppliers, but neglect their respected links. A system contains essential parts or sub-systems with innate behaviours and properties that constitute a functional whole (Ackoff & Gharajedaghi, 2003). Thus, focusing on SC systems, and particularly on both the multi-actor network and their collaboration and interactions (relations) is essential for understanding and potentially improving the AEC industry.

Other researchers, who have been viewing the AEC SC as a system, have enriched the generic descriptions by delving deeper into the system properties, i.e. its components, e.g. nodes of products or actors and their respective relations, e.g. couplings, connections. Winch (1998) described the construction industry as complex product system, which consists of inter-connected and customised elements (or products) where the high degree of user involvement (behaviour) plays an essential role in the innovation process. Dubois and Gadde (2002a) again described the AEC industry as a complex system, where the couplings among the involved actors are closely inter-related, and any change upon one of them may impact the rest of the couplings (inter-relations). They claimed that any effort to organise those couplings in patterns shapes and is shaped by the actors' behaviour, and subsequently, each pattern may solve or create new uncertainties (interdependence) (Dubois & Gadde, 2002a). Therefore, it is essential to analyse not only certain fragments of the construction system but also the behaviour of these respective fragments, the inter-relations among the various actions and the interdependences that develop among those inter-relations.

Describing the construction industry as only a system of interacting actors still is not sufficient to capture all the relevant opportunities and respond to all the challenges in AEC because more variables are into play. Ackoff (1971) underlined that in Management Science, the concept of systems has greatly been tinted from and catered to the particular research viewpoints. Likewise, adopting Systems Thinking to the AEC industry should focus on the AEC system as a whole and not only on its parts in isolation. To analyse a system, we construct a conceptual model, which is – de facto – an abstraction of the reality (Richmond, 2003). Shannon (1975) described and explained modelling based on Systems Thinking: "*the process of designing a model of a real system and conducting experiments with this model for the purpose (...) of understanding the behaviour of the system*". The mismatch between system properties and their conceptualisation are main root causes of system failures (Ackoff & Gharajedaghi, 2003). For this reason and based on the literature review of this chapter, the AEC industry has been conceptualised, abstracted, and modelled as a set of:

– processes (see section § 2.2);
– products (see section § 2.4) and;
– actors (see sections § 2.3 and § 2.6).

From a generic SC perspective, the combination of the systematic analyses in SCs and the shift towards integrated approaches has been suggested. Houlihan (1988) proposed that not only managing the interfaces of the systems is required, but also integrating their multivariate facets (or components). From the references above, it could be deduced, that describing the AEC industry as a system or a network, might be related more to a positivist approach. The term 'System' is quite older than the term 'Network'. The term 'system' originates from the Ancient Greek word sústēma, i.e. organised 'standing' whole or body. The term 'network' pertains more to

TOC

representation approaches and physical constructs, whereas the term 'system' pertains to both tangible and intangible constructs. The Networks have been associated to both positivist and interpretivist standpoints and lately, to both engineering and social sciences, as in management in networks (de Bruijn & ten Heuvelhof, 2008; Klijn, 2008). The thesis applies 'Systems Thinking' by focusing on the concept of 'network', unless underscored differently by the bibliography, across the ensuing chapters.

In this spirit, this thesis has been focused on addressing all these process-, product-, and actor-related complexities of the multi-actor network of the AEC industry. This direction also aligns with the vision of the *International Council for Research and Innovation in Building and Construction*, also known as CIB, from the former name: "Conseil International du Bâtiment" for Integrated Design and Delivery Solutions (IDDS). According to IDDS, to achieve is a maximum impact, AEC needs to transform its capabilities holistically and based on integrated processes, interoperable technology and collaborating people, i.e. organisational issues (Owen, Amor, Dickinson, Prins, & Kiviniemi, 2013). This chapter has attempted a chronological review of the concepts of SCM and BIM, to explore the areas of their potential compatibility and alignment. On the one hand, the concept of SCM has matured from a processual view of managing the complexities of the AEC industry into an inter-organisational concept. On the other hand, the concept of BIM has evolved from a product-related view of managing the complexities of the AEC industry also into an inter-organisational concept. Therefore, it is concluded that inter-organisational considerations suggest common ground for both SCM and BIM constructs. Figure 9 illustrates some advancements and milestones during the evolution of both SCM and BIM constructs to a more actor-related or inter-organisational perspective.

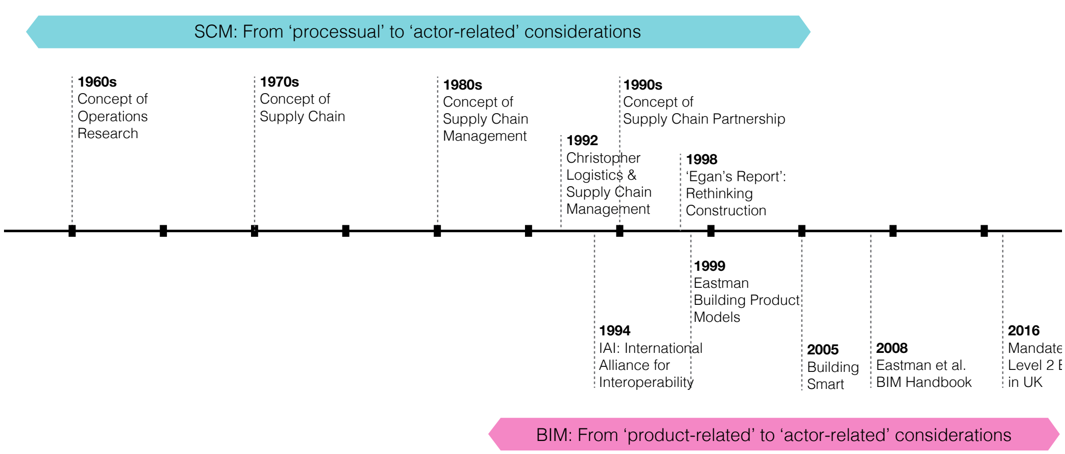

FIGURE 9 The evolution of SCM and BIM concepts from process- and product- to actor-related.

This chapter aimed to reveal the construction challenges that SCM philosophy and BIM technology could potentially manage (RQ#1). To respond to this RQ, first, a short review of similar challenges in other industries and how they were solved by either managerial or technological innovations was presented (section § 2.1). Then, the study on the origins of SC explained the capacity of SCM to deal with processual complexities (section § 2.2). However, the pragmatic impact of SC thinking nowadays emphasises more on balancing the multivariate organisational complexities (section § 2.3). Subsequently, the review of the origins of BIM illustrated the efforts for minimising the technical complexities of building products by regulating and standardising the information flow (section § 2.4). After that, the areas where BIM could be applied as a compatible technology to SCM indicated that BIM could support the material, and information flows among SC systems (section § 2.5). The adoption of BIM affects the organisational structures in AEC and creates an additional mismatch among policy and industry (section § 2.6). Thinking of the AEC as a system is then proposed to support the combination of SCM and BIM, given that both domains have been considered opportunities for managing the AEC (section § 2.7). Table 5 builds on the aspects of complexity defined in Table 3 and illustrates the complexities that could be individually tackled by SCM and BIM as well as on which dimension of complexity the remaining research questions of the study focus.

TABLE 5 Complexities and fragmentation in the AEC industry and the extent that they could be tackled by SCM and BIM as presented in the previous sections; the relation between the alignment of SCM and BIM and the RQs.

	PROCESSUAL COMPLEXITY	TECHNICAL (OR PRODUCT RELATED) COMPLEXITY	ORGANISATIONAL COMPLEXITY & FRAGMENTATION
SCM	2.2 – Logistical perspective of SCM	-	2.3 – Inter-organisational perspective of SCM
BIM	2.5 – Processual opportunities from BIM	2.4 – Object-oriented modelling, i.e. BIM	2.6 – Inter-organisational BIM adoption and maturity
SCM & BIM	RQ#2, RQ#3 and RQ#6	RQ#3, RQ#4 and RQ#6	RQ#4, RQ#5 and RQ#6

§ 2.8 Chapter recapitulation

This chapter described the various challenges in the management of AEC and particularly focused on the issues of processual, technical, and organisational complexities, as well as the inherent and increasing fragmentation of the industry. For this literature review, the concepts of SCM and BIM were analysed chronologically. First, after reviewing the origins and development of SCM philosophy and practices, it was concluded that the structured strategic partnering approaches, i.e. SC partnerships, could form an opportunity for managing the processual and organisational complexities. Although SCM was originally introduced as a concept synonymous with the positivist paradigm, this chapter presented how the concept of SCM has been approached also from an interpretivist standpoint in this PhD research. Accordingly, whereas the concept of SCM has emerged from processual considerations, it has acquired a pragmatic actor-related perspective with regard to the multiple actors involved in the construction networks.

Second, after reviewing the evolution and increasing adoption of BIM in AEC, it is suggested that BIM could potentially offer an opportunity for managing the technical complexities of AEC. The concept of BIM emerged from Building Product Models and therefore, product-related features could be attributed to it, as it is essentially considered a set of “instrumentalities” (Miettinen & Paavola, 2014). Indeed, many of the built-in features of BIM software and current research directions have been focusing on optimising the project performance and subsequently influence the work of various actors. As a construction IT, BIM greatly transforms the various involved actors who adopt and implement it. Therefore, the SCM philosophy is presented as a means to approach the phenomenon of BIM implementation from the various viewpoints of the different multi-disciplinary actors. So far, no theory exists to describe the repercussions of simultaneous SCM practices and BIM implementation.

The chapter advocated that SCM philosophy and BIM technologies could manage not only the processual and product-related dimensions but also actor-related aspects of Design and Construction Management (answer to RQ#1). An inter-organisational or multi-actors’ angle would be an essential for exploring their potential alignment. The alignment of SCM and BIM was explored through the theoretical lens of the conceptual framework of P/P/A, which was defined after the chronological review of the SCM and BIM constructs. Nowadays a combined routine with both BIM and SCM could significantly promote SC integration and reduce its fragmentation, and additionally offer a balanced – or multi-standpoint – attitude towards BIM implementation. Likewise, BIM collaboration process could be greatly enriched from SCM in a middle-out diffusion strategy. This chapter finally provided all definitions and prepared the ground for the subsequent empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6) explorations of the combination of SCM with BIM.

3 Empirical exploration of BIM-based Supply Chains[3]

Chapter summary

Having explored the overview of Supply Chain Management applications in AEC and Building Information Modelling, in recent existing scientific literature, the combination of the two fields is studied in an empirical context. For this reason, five real-world case studies from the Netherlands, where SCM and BIM were simultaneously adopted and implemented, were analysed. The case study research was developed from an explorative and interpretative standpoint. The goal of this study is to understand if and how these two concepts, i.e. BIM and SCM, are further compatible in practice, identify their real-world interdependences, and analyse the BIM implementation process. This chapter will focus on the interdependences between BIM technology and SCM practices in real-world settings (RQ#2).

The real-world applications of SCM and BIM are first analysed as individual concepts and then as one combined approach. From the combined analysis of the two concepts, three main practices of BIM-enabled SC partnering are identified: ad hoc, linear, and distributed. These main BIM-based collaboration patterns contain various features and practices related to the Process/Product/Actor (P/P/A) framework previously emerged in Chapter 2). At the same time, the roles of key actors in the supply chain partnership, e.g. architect, contractor, and suppliers transform and acquire enhanced socio-technical responsibilities. The cumulative impact of BIM-enabled SC practices entails a conceptual merging of SCM and BIM concepts, whose individual structures gradually overlap, e.g. contractual means, and physical interactions. The findings are confronted with relevant scientific literature and discussed as to the inherent research limitations and the possibilities for application in other settings.

3 This chapter is largely based on a paper publised in the journal of Architecture Engineering and Design Management (Papadonikolaki et al., 2016).

§ 3.1 Introduction

The use of BIM increasingly becomes the norm in AEC as numerous professionals use it. BIM offers benefits not only in design management (Elmualim & Gilder, 2014) but also in project management, i.e. time reduction, communication, and coordination improvement (Azhar, 2011), lower costs and fewer returns for information (Bryde et al., 2013). Currently, there are many discussions about the collaboration benefits of BIM (Barlish & Sullivan, 2012; Mondrup, Karlshøj, & Vestergaard, 2012), but without examining BIM implementation in already structured multi-disciplinary teams beyond organisational barriers, such as contractually-bound SC partnerships.

IT, such as BIM, has been suggested as a key enabler of alliances and partnerships (Rezgui & Miles, 2010). SC partnerships, which consist of multiple sets of dyadic relations from the contractor, use SCM philosophy to regulate the material and information flows, by encouraging close project-based collaboration and engagement in future projects. SCM entails a set of practices for integrating the project operations within and across projects. These include partner sourcing, logistics control, quality management, information management and cultural alignment, among others (Vrijhoef, 2011). The traditional SCM practices are susceptible to either lack or redundancy of information. Accordingly, BIM offers possibilities for consistent information sharing and could bring value in managing the information flows. However, despite their apparent compatibility, the concurrent implementation of BIM and SCM is not yet fully explored.

BIM implementation is usually approached from a firm-related level (Succar & Kassem, 2015). Previous research on the collaboration of various AEC actors through BIM (Mondrup et al., 2012; Cidik, Boyd, & Thurairajah, 2014), focuses on inter-organisational settings from a socio-technical perspective, but not in already structured, and trusting relations, such as long-term SC partnerships. According to Mignone et al. (2016), the BIM collaboration process suffers from discontinuities in the geographic disparity of the BIM users, unbalanced team configuration, and incongruent interests. Both SCM and BIM concepts focus on information flows and affect all actors along the project lifecycle. This study reports on simultaneous BIM and SCM implementation in five real-world cases, by analysing both BIM and SCM in one project per SC partnership. The study is relevant not only to BIM researchers and practitioners but also acts as a proof-of-concept of long-standing visions of partnering the SC, e.g. Egan's report in the UK. This chapter aims to understand:

- how BIM implementation unfolds within projects of SC partnerships;
- the emerging interdependences from aligning BIM with SCM.

The background section (§ 3.2) discusses the related work, highlights the research gap and presents the research questions. The study uses exploratory case research (section § 3.3) and presents the results in tables and narratives (section § 3.4). The discussion presents the interdependences of BIM and SCM concepts (section § 3.5) and concludes with implications and suggestions for AEC researchers and professionals (section § 3.6).

§ 3.2 Background, related research, and research gap

§ 3.2.1 Benefits of SCM and BIM

SCM and BIM practices are a hot topic in AEC. SCM is an older concept, which emerged in the mid-80s. It was suggested as a comprehensive management approach to increase customer satisfaction, value, profitability, and competitive advantage (Mentzer et al., 2001). SCM is essentially a management philosophy, and a set of management processes to rationalise the material and information flows (Mentzer et al., 2001). Two main SC thinking schools focus (a) either on the input-output methodology or (b) on inter-firm relationships, e.g. partnerships (London & Kenley, 2001). Gosling et al. (2015) performed a longitudinal study to establish the long-term benefits of partnering and found a direct relation between strategic partnerships and the delivery of consistent performance. This study has focused on SCM practices accompanied by contractual arrangements and strategic visions among the SC partners. Accordingly, the SC partners are divided into internal, i.e. contractually bound or 'strategic partners', and external (Gosling et al., 2015).

BIM is a promising set of technologies for generating, managing, and sharing consistent building information among various AEC actors. The benefits of BIM include several built-in capabilities, such as visualisation and quantity take-off (Eastman et al., 2008). BIM has revolutionised design management by offering fluent visualisation, coherent shop drawings, fast coding and accurate interference detection (Azhar, 2011; Elmualim & Gilder, 2014). Moreover, built-in cost estimating features in BIM applications facilitate the work of quantity surveyors and contractors (Azhar, 2011; Bryde et al., 2013). Succar and Kassem (2015, p.65) describe BIM implementation as a "three-phased approach" that includes readiness (pre-implementation), capability (actual implementation) and maturity (post-implementation) that the firms should develop to engage successfully in BIM. As undoubtedly, BIM adoption steadily increases among practitioners, firms, and countries, the inter-organisational BIM collaboration is a hot topic for the AEC industry.

The use of inter-organisational IT has previously supported construction SCM (Rezgui & Miles, 2010). Regarding the information flows of the SC, BIM could sufficiently regulate the building information flows, because it is a structured data model of building information per se (Eastman et al., 2008) and could offer consistent information flows, through open standards, i.e. Industry Foundation Classes (IFC). BIM has also transformed the materials' cost estimating processes by offering faster and more reliable estimations (Hartmann et al., 2012; Demian & Walters, 2014). From the above, BIM could sufficiently manage the information and material flows of construction. However, given that the BIM-based collaboration is usually asynchronous because it is not a built-in feature (Eastman et al., 2008; Cerovsek, 2011), the various involved parties have to develop new processes, intra- and inter-organisationally. Cidik et al. (2014) highlight that the actors have to pragmatically tailor their 'design workflow' with the BIM models to their particular discipline-related needs.

§ 3.2.2 Inter-organisational challenges from BIM adoption

The involvement of numerous actors complicates further the BIM implementation. BIM transforms the collaboration among clients, architect, and contractors (Sebastian, 2011b). Apart from the designers and contractors, the project initiators (client or owner) and suppliers could play a decisive role as to the implementation of BIM (Nederveen et al., 2010; Porwal & Hewage, 2013). In their study, Volk et al. (2014) acknowledge a significant impact of BIM on maintenance and refurbishment phases of the project lifecycle. This increased number of involved parties in BIM implementation is a factor of inter-organisational complexity.

Apart from the number of interested parties in BIM, the frequency and intensity of their interactions dynamically change during a project. Eadie et al. (2013) analyse BIM implementation throughout the UK construction project life-cycle and claim that "*BIM is most often used in the early stages.*" BIM use during construction creates a mismatch at the division of labour among the partners that increases complexity (Mäki & Kerosuo, 2015). The extent of the actors' involvement throughout the lifecycle of a BIM-based project varies. Cao et al. (2014) have catalogued thirteen different activities where BIM is applicable, e.g. design exploration and coordination, cost estimation, clash detection, quantity take-off. The varying applicability of BIM to phases and activities in AEC influence BIM implementation. To control this varying applicability of BIM across the phases and actors, and prescribe BIM implementation, various National initiatives suggest quasi-contractual means of BIM-related agreements among the actors, e.g. pre-contract BIM Execution Plan' (CPIc, 2013) under the efforts of the UK BIM Level 2, and 'BIM Protocol' Norm issued by the Dutch Government Building Agency

(GBA) (Rijksgebouwendienst, 2012), both of which are inspired from the Norwegian equivalent 'BIM Manual' (Statsbygg, 2011).

In a project with numerous BIM-using firms, the dynamics of the project-based BIM goals constantly change, given that the firms carry various BIM readiness, capability and maturity levels, because of their different disciplines and sizes (Succar, Sher, & Williams, 2012; Succar & Kassem, 2015). Mondrup et al. (2012) highlight that the varying capabilities among the collaborating firms often result in misunderstandings. Harty and Whyte (2010) claim that there is a lack of understanding of the role that digital technologies, such as BIM, play in projects, and especially how the actors' BIM knowledge is accordingly transferred. Meanwhile, a recurring challenge has been the need to inspire and retain trust throughout BIM-based collaboration among extended multi-disciplinary teams (Miettinen & Paavola, 2014; Cao et al., 2015). Trust also influences the sharing of risks and rewards and together with commitment leads to closer SC cooperation (Mentzer et al., 2001). Therefore, BIM could potentially overcome these inter-organisational barriers if applied within already structured environments, such as SC partnerships. Accordingly, the structured environment of SC partnerships could offer fresh insights into BIM implementation.

§ 3.2.3 Research gap regarding BIM-enabled SC partnerships

The previous sub-sections underlined that BIM technology and SCM theory could support one another and counterbalance certain inter-organisational challenges. Nowadays, the criteria of SC partner selection process have transformed from price- to collaboration-based (Pala, Edum-Fotwe, Ruikar, Doughty, & Peters, 2014; Sporrong & Kadefors, 2014) or require the use of IT, e.g. BIM (Mahamadu, Mahdjoubi, & Booth, 2014; Yin, Tserng, Toong & Ngo, 2014). Simultaneously, the size of the inter-organisational teams, the intensity of their interaction and trust are non-negligible parameters for BIM implementation. This study explores the real-world combination of BIM and SCM concepts. This combination, hereafter referred to as BIM-enabled SC partnering, denotes practices of contractually-bound SC partnerships that apply BIM.

From the above, there is a lack of understanding of how the mutual dependence, i.e. interdependence, of BIM and SCM could facilitate a SC to achieve its goals through BIM. First, BIM implementation resembles a complex network, because various actors are involved, beyond the design team, such as clients and asset owners (Love, Matthews, Simpson, Hill, & Olatunji, 2014; Son, Lee, & Kim, 2015a) and suppliers. Second, the existing approaches to alliances tend to be more IT-driven and less inter-organisational even in long-term collaborative ventures, such as SC partnerships (Rezgui & Miles, 2010). Therefore, this chapter seeks to explore the *RQ#2: What are* *the interdependences between BIM technology and SCM practices in real-world settings? (Chapter 3)*. It further divides it into two sub-questions and explores the following:

- How is BIM implemented within projects of SC partnerships?
- What are the interdependences between the concepts of BIM and SCM?

§ 3.3 Methodology

§ 3.3.1 Research rationale

Case study research is a popular research method, which focuses on in-depth analysis of phenomena by providing a "real-life context" (Yin,1984). This study used case study methods for exploring the alignment of SCM with BIM concept in their "natural setting" (Benbasat, Goldstein, & Mead, 1987), aiming to provide insights into other inter-organisational BIM settings. Case studies emphasise on the richness of the analysis, rather than a potential generalisation. However, as Bengtsson and Hertting (2014) stated, the case study methods could facilitate a potential generalisation based on "expectations about similar patterns of thinly rational action and interaction in similar contexts", i.e. other BIM-enabled SC partnerships.

The qualitative case study research was used for two main goals. First, the goal was exploratory to respond to the 'how' research question. Second, to respond to the 'what' question, the goal was explanatory, i.e. to evaluate the practical interdependences of BIM and SCM. Throughout this chapter, these different goals are underlined by different data analysis methods. Before presenting the case study design and protocol, a brief discussion of the wider research setting and the case selection criteria will intervene.

§ 3.3.2 BIM and SCM in the Dutch AEC

The Dutch AEC was selected as the setting of these qualitative case studies on the alignment of BIM and SCM. Three reasons explain the selection of the Dutch AEC: the (a) attention given to partnering and SCM, (b) affinity to innovation regarding BIM, and (c) idiosyncrasy of the Dutch market that could potentially allow for generalisation.

First, the concept of SCM has been diffused in the Netherlands, following the *Rethinking Construction* movement, which originated in the UK around 1998. Later, the Dutch firms looked collaboratively into cost reductions and long-term mutual financial benefits (Vrijhoef, 2011). Second, the Dutch AEC is keen to adopt integrative innovations, such as IPD, BIM, and SCM (Wamelink & Heintz, 2015). The Dutch construction market has been quite proactive in BIM-related initiatives, for example in developing BIM assessment tools after popular demand of AEC firms (Sebastian & Berlo, 2010). Third, according to Dorée (2004), the "*efforts to reduce risks and uncertainties are engrained in Dutch culture*" and this could explain this market's eagerness to self-regulate regarding BIM. Given that the Dutch AEC has been proactive and consensus-seeking, any lessons-learned from this smaller and reactive market might accordingly reflect future trends to larger construction markets.

§ 3.3.3 Case selection

A set of selection and diversity criteria was used to ensure the relevance of the cases to BIM and SCM concepts and additionally allow for diversity, research reliability, and generalisation. Table 6 contains these criteria:

TABLE 6 Case selection and diversity criteria.

GOAL	CRITERIA	
	Criterion	Explanation
Selection	Team	A multi-disciplinary SC partnership across engineers, contractor and supplier.
	History	The SC partners had collaborated before on at least one other project and one or more contractual relations, i.e. framework agreement, exist.
	Vision	The SC partnership expresses a clear vision for future collaboration.
	Technology	Use of BIM-based tools from at least one SC partner.
Diversity	Type	Building construction: multi-functional (MF), housing or utility building.
	Scale	Small (up to 2,000 m2) to large (more than 20,000 m2) projects.
	Size	Small-medium Enterprises (SME) or Multi-National Companies (MNC).
	Boundaries	Local or national character of the SC partnership.

With regard to the technology used by the involved firms, at least one case firm should implement BIM. Given that in the literature, there are a lot of examples where BIM is implemented by only one or two actors, ideally more than one BIM-using actor would be sufficient for this study. As it happens, at least five actors per case used BIM. A sample of fourteen construction projects in the Netherlands was evaluated as to the above criteria by a short intake interview, before the official launch of the study. Figure

10 illustrates the various recruited and followed case studies. Afterwards, five cases that fit the research timeline were selected. All cases were studied between Definitive Design and Pre-Construction. Both recently completed and ongoing cases were explored, to avoid any biases pertinent to impression management or retrospective sense-making (Eisenhardt & Graebner, 2007, p. 28). Leonard-Barton (1990, p. 255) claimed that this type of synergy between completed and ongoing cases increases research validity. For confidentiality, the cases are referred to as A, B, C, D and E, sorted in recruitment order.

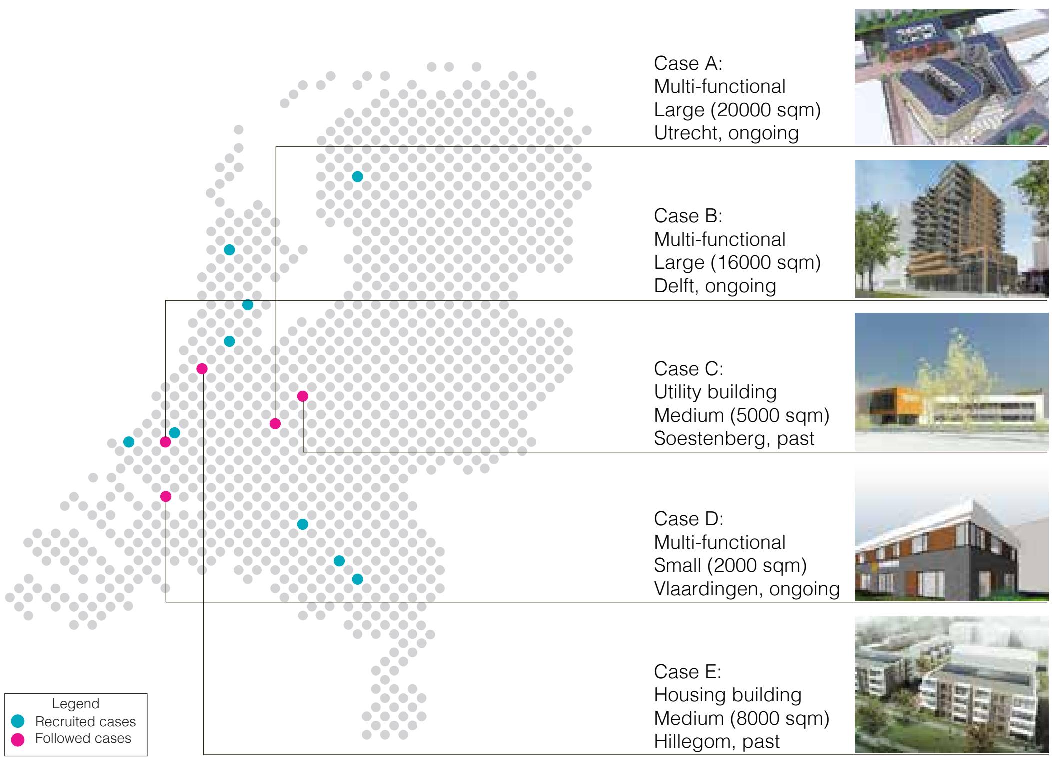

FIGURE 10 Initial set of recruited cases and the final sample of the five followed case studies.

Case study A is a complex Multi-Functional (MF) project, which consists of three buildings with 255 residential units, offices and commercial spaces. The complex is next to a canal, and its construction is expected to last sixteen months. Case study B concerns a large housing tower, with 83 flats and high technical complexity (Figure 11a). Case study C is a recently completed project, which included an industrial building, exhibition, and offices. The construction of project C lasted about six months, due to a high degree of repeatability and off-site fabrication (Figure 11b). Case study D concerns a small and simple industrial and office space and its construction is expected to be complete in nine months. Case study E is a recently completed project with 44 residential units arranged in two rectangular volumes. Overall, all contractors in the five cases were Design-Build contractors.

FIGURE 11 Under-construction housing tower building project of case B (left), and the interior of utility building of case C (right).

Table 7 shows an overview of the cases' selection and diversity criteria. The first column to the left contains the project identifier. The following four columns include the selection criteria. The last five columns contain the diversity criteria and projects' status. The exploration observed repeatable and distinct patterns, and thus, the case selection was considered saturated, as it will be explained in section § 3.4.

TABLE 7 BIM-enabled SC partnerships case description as to case selection and diversity criteria.

	SELECTION CRITERIA				DIVERSITY CRITERIA				
	Multi-team	History (projects)	Vision	BIM	Type	Scale	Size	Boundary	Status
A	Yes	2	Unclear	Yes	MF	Large (L)	MNC	Local	Ongoing
B	Yes	10	Yes	Yes	Housing	L	SME	National	Built
C	Yes	7	Unclear	Yes	Utility	Mid- (M)	SME	National	Built
D	Yes	8	Yes	Yes	Utility	Small (S)	SME	National	Ongoing
E	Yes	3	Yes	Yes	Housing	M	MNC	Local	Built

MF: Multi-functional project, MNC: Multi-national Companies, SME: Small-medium Enterprises.

§ 3.3.4 Case study design

From the five cases, data were collected from interviews and observations in three phases:

- Phase I: SCM analysis: Questions about history, and vision of SCM;
- Phase II: BIM analysis: Questions about BIM implementation and application areas and observation of 'BIM meetings';
- Phase III: Reflection on BIM-enabled SC partnering: Questions about the outcome of the practices.

The questions for each Phase are included in Appendix A. The data from the interviews of Phase I and II were analysed with descriptive statistics, because the questions were closed, and presented in a tabulated form to facilitate the case comparison. The open questions of Phase III were analysed with qualitative analysis software using free codes, regarding aspects of BIM and SCM. Phase III included the feedback from the three completed cases.

§ 3.3.5 Case study protocol

Given that a Supply Chain is a distributed network, an equally distributed data collection method was used. The selected method could be considered a corrective action to the existing SCM theories, which has been focusing more on isolated dyadic relationships neglecting any holistic considerations, as Fernie and Tennant noted (2013, p. 1049). This research did not concentrate on the 'focal' firm of the SC, instead sought equivalent input from all firms. The projects were followed for between 12 and 18 months, depending on the scale of the project, and 44 professionals from 31 different firms were interviewed. In all firms, the number of employees interviewed depended on their availability and their knowledge and affinity to the concepts of SCM and BIM. The data collection involved four activities:

- 13 group interviews from the SC actors;
- Review of project documents, i.e. five SC contracts and three BIM protocols;
- Three on-site visits and six meeting observations;
- 13 individual interviews with case participants (interviewees).

All cases included group interviews among the internal SC or the whole SC. The group interviews lasted one hour and a half and aimed at limiting the informant bias and reflecting on their collective understandings. First, the group interviews were initiated with a short introduction about the position of the interviewees inside their firm. Subsequently, each question was addressed to the first interviewee to the right of the interviewer and then next to their right had the opportunity to add to or improve the answer. This process was repeated until all interviewees were satisfied with the collectively registered answers.

The individual interviews were shorter (45 minutes long) and took place after the group interviews to cross-evaluate the previous findings and to deepen the case exploration and mitigate any interviewees' biases. Multiple informants, with diverse functions, e.g. BIM modellers and project managers were interviewed per organisation. Table 8 shows per case the data collection phases and data sources. Not all cases had exact the same data collection phases and sources, given that some cases were past cases and the availability of the interviewees differed from case to case.

TABLE 8 Data collection sources per case and an indication of the phase where it took place respectively.

	PHASE I	PHASE II	PHASE III
A	1, 2, 3, 4	1, 2, 4	Ongoing project
B	1, 2, 3, 4	1, 2, 3, 4	1, 5
C	1, 2	1, 2	1, 5
D	1, 2, 4	1, 2, 4	Ongoing project
E	1, 2, 3	1	1, 5

1: Collective interviews, 2: Analysis of documents, 3: Visit site, 4: Observation of meetings, 5: Individual interviews.

All interviews had the same preparation, administration, and information handling. Before the interviews, all interviewees had the same information about the study via a template email sent. All relevant project documentation was reviewed beforehand. Question hand-outs were administered during the interview. The language was English or Dutch. The interviews were recorded with the interviewees' permission to facilitate the transcription. The interviewees welcomed the used of information for research but preferred to stay anonymous.

§ 3.4 Case results: Description, analysis and interpretation

§ 3.4.1 Description and analysis of SCM (Phase I)

The cases had various SC team compositions and spread along different project phases. The partners varied depending on the technical challenges of the project and SC investment ambitions. In all projects, the contractor was internal SC actor. The rest of internal SC actors belonged in both the front SC part (from initiation to design), e.g. clients and designers and the back SC part (from construction to operation), e.g. installation firms and suppliers. The team of the internal SC actors, up until Pre-Construction, was formed as follows:

- Case A: The contractor, structural engineer, energy advisor, heating, energy and plumbing, client, and facility manager firms.
- Cases B, C, and D: The contractor, architect, structural engineer, steel sub-contractor and suppliers, e.g. windows, cladding, roof, firms. For case C, the client (investor) was also an internal SC actor.
- Case E: The contractor, architect, structural engineer, heating engineering and installation firms.

Table 9 illustrates the SCM activities per case. The first column to the left contains the project identifiers (A, B, C, D and E). The rest columns include SCM activities for achieving SC integration. Vrijhoef (2011, p. 225) categorises eleven activities that could incite greater integration among the SC actors. The cells contain the descriptions 'Yes' and 'No' when a particular activity was on not applicable in the cases, respectively. The data were obtained from the closed questions of the intake interview and Phase I (see Appendix A). The last column calculates the outcome of the factors present in each case and the total number of factors to present the relative SCM maturity across the SC partnerships.

TABLE 9 SCM activities that contribute to SC integration (column list adapted from Vrijhoef [2011]).

	REPETITIVENESS	INTEGRATION OF BUSINESS ACTIVITIES	PARTNER SOURCING	INTEGRATION OF OPERA-TIONS	LOGISTICS CONTROL	QUALITY MANAGEMENT	INFORMATION EXCHANGE	PRODUCT DEVELOPMENT AND DESIGN	MARKET APPROACH AND MARKETING	CULTURAL ALIGNMENT	HUMAN RESOURCE MANAGEMENT	TOTAL NUMBER OF PRESENT FACTORS
A	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	7/11
B	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	8/11
C	No	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	No	6/11
D	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	8/11
E	No	No	Yes	No	Yes	No	Yes	Yes	No	No	No	4/11

§ 3.4.2 Description and analysis of BIM (Phase II)

BIM implementation across phases

The cases presented BIM use in various instances. BIM was used in the Preliminary Design (PD), Definitive Design (DD) and Technical Design (TD) phases for every case. At times, BIM was used in Construction for generating the materials' quantities and volumes and planning and optimising of the site logistics (cases A, B, and D). In the cases A, B, and D they aspired to use BIM during Operation. In all cases, BIM was used by the architects, structural engineers, MEP, contractors, and some suppliers. BIM was used only during a few of the areas where – according to literature – it is usually applicable (Cao et al., 2014). Table 10 presents an overview of the BIM applications, catalogued by Cao et al. (2014). The first column to the left contains the project identifier. The table cells contain the descriptions 'Yes' and 'No' when a particular BIM application did or did not take place, respectively. The data in Table 10 have derived from the questions of the intake interview and of Phase II (see Appendix A) and live observations. The most popular BIM applications were three-dimensional (3D) representation, design coordination, clash detection (see a typical clash detection session in Figure 12), and quantity take-off. BIM was rarely used for cost estimation, energy simulation or site management.

TABLE 10 BIM application areas per SCM project (column list adapted from Cao et al. [2014]).

	SITE ANALYSIS	DESIGN EXPLORATION	3D REPRESENTATION	DESIGN COORDINATION	COST ESTIMATION	ENERGY SIMULATION	CLASH DETECTION	CONSTRUCTION SYSTEM DESIGN	SCHEDULE SIMULATION	QUANTITY TAKE-OFF	SITE RESOURCE MANAGEMENT	OFFSITE FABRICATION	TOTAL NUMBER OF PRESENT FACTORS
A	No	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	7/12
B	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	7/12
C	No	No	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	5/12
D	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	6/12
E	No	No	Yes	Yes	No	No	Yes	No	No	No	No	No	4/12

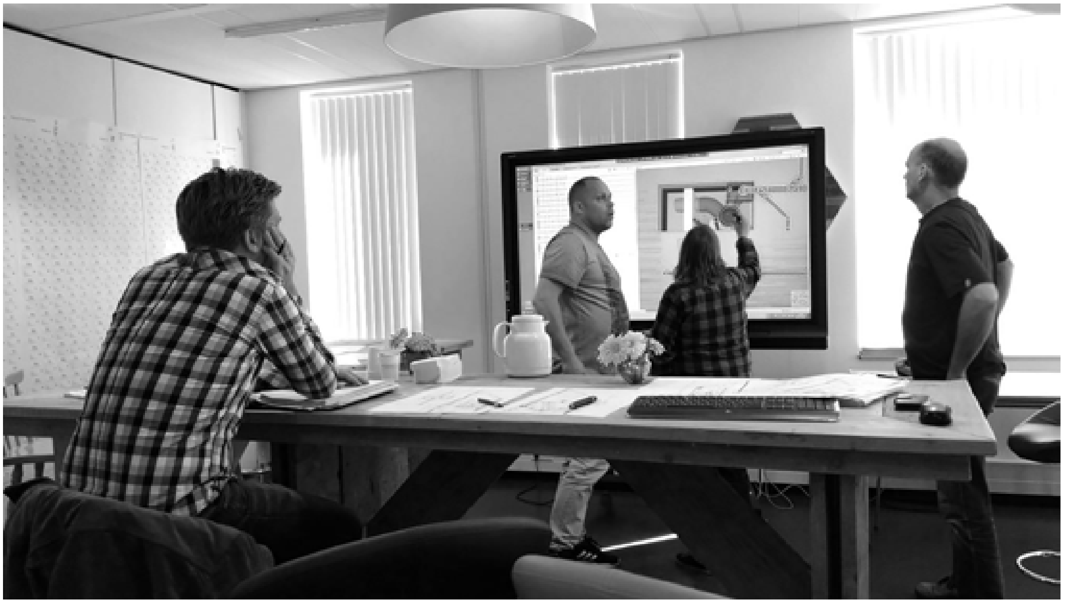

FIGURE 12 Typical clash session with the installation disciplines (Case A).

SC collaboration via BIM

The firms that participated in the study displayed varying BIM readiness levels. In decreasing order of BIM experience, the SC of case E had two past BIM-based projects, A had one and B, C, D had sporadic BIM applications respectively. The BIM

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implementation was evaluated by analysing the physical BIM meetings and the digital collaboration processes. The five cases were found to display three levels of BIM-based collaboration: *ad-hoc*, *linear* and *distributed*, in increasing order of sophistication. The term 'pattern', borrowed from the 'Design Patterns' of Alexander's et al. (1977) is used to indicate the potential reusability of solutions across similar contexts. *Ad-hoc* or impromptu BIM collaboration was observed in case E, where BIM was not a contractual requirement. The term 'ad-hoc' was used to describe this pattern because the actors' activities were not pre-defined or intentional and the actors appeared to be learning-on-the-job. Few actors used BIM, and the contractor was responsible for coordinating their BIM models occasionally by exchanging proprietary (native) BIM files. The exchange of two-dimensional (2D) drawings, frequently and iteratively, was greatly encouraged and thus, the building information was unevenly shared among the SC actors.

Linear BIM collaboration pattern was observed in projects C and D. The term 'linear' was used to describe this pattern because the workflow was sequential. Most actors used BIM, apart from some suppliers. The BIM collaboration took place by merging 'aspect (or reference) models' to one with model checker software, via IFCs. The collaboration is described as linear because the contractor, who was in charge of model's federation, had separate and on-demand BIM sessions with each actor, similar to the 'over-the-wall' process, and informed the rest by e-mails. The building information was quite uniformly shared among the SC partners, but some redundancy was observed in the exchange. The SC actors in these cases relied more on the underlying informal relations of their SC partnership.

Distributed BIM collaboration pattern was observed in case A and B. The term 'distributed' is used because control was exerted from various actors. The contractor was responsible for merging 'aspect' models weekly with model checker software, similarly to the afore-described *linear* process. The coordination of their activities was achieved by hosting pre-scheduled joint *BIM meetings*, and predefined co-locations, i.e. performing various multi-disciplinary activities in the same location. The clients occasionally attended these sessions to ensure their requirements were met. The building information was more uniformly shared among the SC actors. Table 11 summarises the above three categories, based on data from the cases, i.e. live observations of the BIM sessions, document analysis of the BIM protocols, and from the answers received to the questions of Phase II (see Appendix A). The input for the various columns is not only a binary answer, but also it takes into consideration the intention of the involved parties; that is whether the various aspects were on-demand or pre-defined.

TABLE 11 Observed patterns of BIM-based collaboration among the SC partnerships.

DIMENSION	OBSERVED FEATURE	PATTERN		
		Ad-hoc	Linear	Distributed
Actor	BIM as a contractual requirement	-	-	Yes
	BIM-savvy strategic partners	-	Yes	Yes
Process	BIM-related meetings	On-demand	On-demand	Pre-scheduled
	Co-location practices	-	On-demand	Predefined
	Use of Common Data Environment	-	-	Yes
Product	Use of firm-based BIM Protocol(s)	Yes	Yes	-
	Compliance with one BIM protocol	-	Yes	Yes
	Model checking tools	-	Yes	Yes
	Information exchange file type(s)	CAD/PDF, Native	CAD/PDF, Native, IFC	Native, IFC
	Deliverable file type(s)	CAD/PDF	CAD/PDF, IFC	CAD/PDF, IFC

§ 3.4.3 Reflection on BIM-enabled SC partnerships (Phase III)

The cases were not at the same stage when recruited. Given that they had diverse briefs and end dates, only three projects have been completed to now. The reflections on BIM-enabled SC partnering were obtained from the built projects (B, C, E).The sample was representative because it featured all three emerged BIM collaboration patterns, i.e. *ad-hoc, linear* and *distributed*. The actors' reflections first present the project's outcome, second the inter-organisational relations, and third conclude with their future approach to improving the alignment of BIM and SCM.

Case B (distributed pattern) was delivered on time and budget, but some time pressure was reported and attributed to the initial commercial decisions taken by the tender managers. Given that the various partners had very dissimilar BIM skills, BIM was not smoothly implemented. For example, some construction mistakes were made, and were discovered and corrected on site (brick fittings in the pre-cast concrete).The architects and the mechanical engineers reported that they were learning from project to project: "*Everyone wants to optimise their own product.*" Concerning the practices to support BIM implementation, the architects reported that: "*with the co-locations it was easier than calling to arrange something. We learned a lot by making errors, and we want to sit together more frequently now*". In the future, they want "*to plan in greater detail when each company receives and delivers their BIM*" (Architect-BIM modeller). Regarding SCM, the main challenge was that some actors prioritised their intra-organisational planning rather than respecting the joint SC planning. Thus, the partners agreed that in the future they would "*try to involve the suppliers who are SC partners even earlier in the design process.*" Concerning BIM, the partners concurred that they should clarify their agreements about the Level of Detail (LoD) in advance and improve their BIM strategy.

The project of case C (linear pattern) was delivered timely with no cost overruns. However, the partners concurred that all of them had "*unfortunately underestimated the project complexity*." From the partners, only the cladding supplier was advised to improve their quantity and cost calculations. Poor time management was occasionally reported. The contractor advised the steel sub-contractor to "*respect the agreed deadlines when delivering the drawings*." TD was the most challenging phase, and to improve it, closer collaboration between architect and structural engineer was suggested. The partners unanimously decided to densify the joint sessions and choose an appropriate location and period for team co-location in the future. Concerning their daily communication, the partners noticed that "*exchanging 2D drawings was most beneficial because it was faster and more efficient for all*." The contractor suggested that the architects would standardise their mostly used technical details in BIM. Regarding the composition of the SC partnership, the contractor's site manager stated: "*we would like to partner with more specialisations, we are looking for it, but none of our preferred partners look suitable,*" as to price flexibility and cultural alignment. They agreed mostly to revise their BIM, rather than SCM strategy in the future.

The project of case E (ad-hoc pattern) was delivered timely, but the SC partners had to absorb cost overruns that exceeded the tender agreement with the client. The client (external SC actor) stated: "*We do not use BIM in our organisation, but we view it as a method to minimise the faults and improve the quality of the chain*." The senior architect stated: "*the combination of SCM and BIM is very focused on the second stage of design phase (and) there are benefits that have not been exploited yet*." He added that whereas "*not all architects are really aware of what SCM could mean for their work*," his firm is "*actively pursuing more SC collaborations*." Further, the contractor's site manager stated that "*BIM is the future; it is efficient and eliminates extra costs, yet they double-checked all calculations manually for the quantities*". BIM was used only during PD, DD, and TD. The partners exchanged 2D drawings and native BIM files. Some firms had their own BIM protocol, but no joint BIM protocol plan was applied. They only analysed the clashes and observed some improvements during the TD phase. Concerning the SCM strategy, the contractor's tender manager mentioned: "*we are very satisfied (but) we are now busy with changing the composition of the chain (…) we want more proactive partners*". The actors concurred with: "*we have never performed a project evaluation among the chain partners (…) it is not yet in our culture*" but they agreed on engaging with it in the future. The senior architect stated: "*our BIM methodology that we have to develop it all the time (…) because all the partners are also improving their methodology*". This partnership plans to considerably refine both their future BIM and SCM strategies.

Table 12 summarises the reflections from the built cases (cases B, C, E) in support of the paragraphs above. The narratives are organised around the most common applications of BIM and SCM, previously presented in Table 9 and Table 10. In case B, all partners were equally enthusiastic about both BIM and SCM, and they presented the highest level of SC cultural alignment. Case C displayed a balanced vision for BIM and SCM practices. Case E had a disproportionate focus on BIM over SCM, although BIM was not implemented in its full capacity. For example, the contractor was more BIM- than SCM-driven, whereas the architect was equally SCM-driven and BIM-enthusiast. In all cases, BIM played a role in facilitating the popular SCM activities, such as selecting partners, ensuring quality and sharing information (see Table 12)

TABLE 12 Convergent testimonials about areas of improvement from BIM-enabled SC partnering (built cases).

	FACTOR	CASE B	CASE C	CASE E
SCM	Partner sourcing	*"In the future, we will try to involve the suppliers who are SC partners even earlier in the design process"* (Contractor)	*"For all the sub-contractors, we make contracts, and we ask for BIM models. (...) But also price is important"* (Contractor)	*"When we had to make the selection of the partners, (...) we just let them tell us on a presentation what they understand about SC"* (Contractor)
	Quality management	*"With BIM, everyone wants to optimise their own product"* (Architect) With SCM, we do not have to think which party is less expensive. We strive for quality and because we want to know what we have in common, a kind of blind trust* (Structural engineer)	*"For us, quality is synonymous with BIM use"* (Architect)	*"We view it (BIM) as a method to minimise the faults and improve the quality of the chain"* (Client) *"BIM was more important for quality management than SCM"* (Architect)
	Information exchange	Especially in BIM and SCM, we are much more dependent on information from others* (Steel sub-contractor)	We went back to 2D drawing use for communication; it works faster and efficiently for all* (Cladding supplier)	-
	Cultural alignment	*"Together with the other partners we are learning a lot about BIM"* (Mechanical Engineer) And we know each other, also begin to know each other personally and it is also fun to have this relationship* (Steel sub-contractor)	*"If they (other partners) want to be still preferred suppliers, then that (BIM) is what we want"* (Contractor)	*"We always ask them how they stand. (...) We ask: 'are you ready to show us all the cards?'"* (Contractor)

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TABLE 12 Convergent testimonials about areas of improvement from BIM-enabled SC partnering (built cases).

	FACTOR	CASE B	CASE C	CASE E
BIM	3D representation	-	-	*"BIM did play an important part in 3D representation, not just in engineering"* (Architect)
	Design co-ordination	*"With the co-locations was easier than calling to arrange something. We (...) want to sit together more frequently now"* (Architect)	*"The BIM design process, (...) it is not really optimal yet, but we are getting there, (...) we have to make the distance smaller among the partners."* (Architect)	*"That (design co-ordination) went far because of the supply chain, together with BIM"* (Architect)
	Cost estimation	*"In this project, we only did the modelling, we did not do a lot of analyses, we want to improve that in the next"* (Contractor)	"All calculations were successful apart one supplier* (Structural engineer)	-
	Clash detection	*"We had a clash session with the concrete supplier and in ten minutes we could be discussing issues all around the building that are influenced by it because the building is so complex"* (Architect)	*"We invite some partners whose responsibility it is and just make clash session only with them. It is faster."* (Contractor) *"Maybe in an ideal process we put all the partners altogether"* (Architect)	-

* Translated from the Dutch by the authors.

§ 3.4.4 Interpretation

Use of BIM within SC partnerships

BIM implementation deeply influenced the SC partnerships. About half of the interviewed firms claimed that adopting BIM was an internal decision, often made since 2000, to serve their intra-organisational need for advanced IT. These firms used it in about half of their projects, included it in their business plans and advertised their BIM-readiness on the market. The other firms stated that BIM adoption was a natural but external decision because they had to meet client and market demands. In case E, the contractor performed an unofficial competition with a brief and presentation among their preferred partners to select the most BIM-savvy firm. Thus, there are both internal and external reasons for why the phenomenon of BIM-enabled SC partnering has unfolded.

In all cases, the SC partnerships were supported, even when non-BIM using partners were selected. The non-BIM users either followed a traditional process aside or were learning on-the-job. The BIM-using partners of cases A and E helped the less experienced partners during extra BIM training sessions. In case B, the steel sub-contractor, who was an internal SC partner, had hired a BIM drafting company to deliver their input in BIM. However, there was an apparent mismatch on the vision for BIM and its actual implementation, e.g. in case E, the BIM capacity of the SC actors was disproportional and *ad-hoc* BIM collaboration was deployed (see Table 6). Whereas in case B, not all SC actors were BIM-ready (e.g. sub-contractor), but the BIM collaboration was *distributed* and sophisticated.

Use of SCM in BIM implementation

Written regulatory documents, i.e. framework agreements, are standard in SCM practices. The cases also customised their BIM protocols based on the Dutch GBA's BIM Norm (Rijksgebouwendienst, 2012). The SC partners used BIM protocols to define their BIM process aside the existing SC contracts, which defined their financial obligations and rewards. The cases B and D jointly customised the norms to the project needs. The BIM protocols described the BIM-related project goals, modelling stages, LoD, timelines, deliverables, and agreements for their meetings. However, not all cases used the protocols in the same manner, as the Dutch GBA does not mandate their use. There was a mismatch between firm-issued and jointly decided BIM protocols among the SC actors (see Table 11).

Apart from the written agreements, the SCM practices influenced the physical BIM collaboration. In cases A, B, and D one or more joint meetings with all partners were held, i.e. *BIM meetings*, *BIM Design & Engineering meetings* or *BIM Design sessions*. These meetings resembled the pull-planning sessions, which also took place in cases B, C, and D, as to the setting, informal character, established underlying trust, and consensus-seeking orientation. Figure 13 illustrates a typical pull-planning session, where all actors' input was taken into consideration. The BIM meetings were mandatory for all partners invited, held weekly or fortnightly and lasted about two hours. After the sessions, the BIM coordinator, who was often from the contractor (cases A, C, D, and E) or the architect (case B), was responsible for sharing the session results. However, the scheduling, content, and participation in the BIM meetings was varying per case and per BIM collaboration pattern (see Table 11).

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FIGURE 13 Typical pull-planning session for construction planning (Case C).

Cumulative case results

The cases offered insights into the adoption and implementation of BIM-enabled SC partnering. Table 13 summarises the results. The first column to the left contains the case identifiers. The next contains information on project type and scale. An analysis of BIM use as to the actors and application areas (from Table 10) is shown in the subsequent column. The following two columns show SCM adoption as to the actors and undertaken SC activities (from Table 9). The column before the last contains the description of the observed collaboration pattern of the BIM-enabled SC partnership (from Table 11). The last column to the right contains the reflection from the case narratives about how the interdependent BIM and SCM strategies will be deployed in the future.

TABLE 13 Findings of the analysis of the selected projects with BIM-enabled SC partnering.

CASE DESCRIPTION		BIM ANALYSIS		SCM ANALYSIS		BIM-ENABLED SC PARTNERING	REFLECTION
Type and scale		Actors using BIM	BIM application areas	Internal SC actors	SCM application areas	BIM-based collaboration process	BIM & SCM future strategy
A	MF; L	9/10	7/12	6/10	7/11	Distributed	(Ongoing)
B	Housing, L	9/11	7/12	8/11	8/11	Distributed	Improve BIM strategy
C	Utility; M	6/8	5/12	5/8	6/11	Linear	Improve BIM strategy
D	Utility; S	7/9	6/12	5/9	8/11	Linear	(Ongoing)
E	Housing; M	5/8	4/12	6/8	4/11	Ad-hoc	Improve BIM & SCM

§ 3.5 Discussion

§ 3.5.1 BIM implementation in SC partnerships

The study identified three patterns of BIM implementation from the SC partnerships: *ad-hoc, linear* and *distributed*. These patterns emerged from the observations of repeated physical and digital structures and processes, e.g. co-locations, written agreements and information exchange, and to the best of found knowledge, has not been included in existing literature. Apart from considering BIM implementation as a set of readiness, capability, and maturity levels for individual firms (Succar & Kassem, 2015), BIM implementation entails various repeated patterns of collaboration. The emerged patterns pertain to an inter-organisational level and highlight the potential disparities among firms with different BIM capacity (Mondrup et al., 2012). Moreover, the *ad-hoc, linear* and *distributed* patterns offer more information than the three levels of the well-known UK BIM maturity wedge (GCCG, 2011), because they include not only the format of the exchanged information but also its physical and digital conditions, which emerged from SCM practices. Given that collaboration with BIM requires a collective effort, this study contributed on how the firms' BIM readiness, capability and maturity could be translated into a networked and interdependent environment. For example, case E displayed a mismatch regarding firm-based BIM readiness and BIM implementation among the partnership, given that whereas some firms had past BIM experience; they were exchanging native files with their less experienced partners (Table 11). The above mismatch outlines implications for the practitioners, since the firms would potentially choose BIM-ready partners to utilise the potential of BIM fully and fine-tune their BIM capacities according to different disciplines and firm sizes (Succar et al., 2012), and the specific project BIM scope.

The *linear* and *distributed* patterns featured an aggregation and checking of the reference models by an appointed BIM coordinator in the form of open standards, i.e. IFC. The *distributed* collaboration pattern was considered the most sophisticated because it was additionally supported by pre-defined types of physical interaction. The *distributed* patterns underscored the discussions of Miettinen and Paavola (2014) about the misconceptions for a single BIM, and that the BIM-based information exchange is, actually, asynchronous (Cerovsek, 2011). The *distributed* BIM-based collaboration pattern allowed for quite consistent information flows, via the IFC, and additionally provided the SC partners with the ability to use their preferred software. The three patterns were also directly proportional to the number of BIM application areas of Cao et al. (2014) (Table 13). A surprising finding was that the BIM-based collaboration patterns were not related to the number of undertaken SCM activities (Table 13), which could suggest that BIM implementation in SC partnerships is currently transitioning and that the partners rely heavily on their SCM relations, i.e. shared history and vision, rather than BIM. Whereas the case sample is small and cannot be generalised, an important inconclusive statement could be that the level of SC integration did not correspond to the sophistication of their BIM-based collaboration.

§ 3.5.2 Interdependences between BIM and SCM

The reported benefits of BIM are numerous, as Barlish and Sullivan (2012) and Bryde et al. (2013) suggest. This study presented how processes and products used for SCM in contractual long-term SC partnerships could support and improve BIM collaboration to attain the acclaimed BIM benefits for the actors. The cases presented real-world evidence on the use of hybrid practices to support the digital technologies, i.e. BIM (Harty & Whyte, 2010). First, BIM implementation, which requires close collaboration among multi-disciplinary professionals, was supported by on-demand or frequent co-locations (Table 11) (cases B, C, D), and even more frequent co-locations were unanimously desired in the actors' reflections for the future (Table 12). These meetings could increase the commitment of the SC partners, which accordingly increases trust in the SC partnership (Mentzer et al., 2001). Second, the BIM implementation was supported by quasi-contractual means, usually adopted in SCs. The 'BIM protocol', or BIM Execution Plan facilitates the definition of 'what' to exchange, LoD, and modelling phases and thus improves the challenges pertinent to design ownership (Cidik et al., 2014). However, whereas these protocols are part of National policies, in the cases, they were project-dependent. The shared vision, history, and experiences from SCM enriched the definitions of 'how' and 'when' to interact, e.g. issuing specifications and hosting regular pre-scheduled physical meetings. The use of formal agreements, such as BIM protocols and agreements for using standards (Table 11), could inform the process to achieve consistent information-sharing. Thus, SCM practices enriched BIM with processual (co-locations) and product-related specifications (protocols) for more efficient BIM implementation and collaboration among the actors.

The popularisation of BIM induces changes in the SCM practices. The traditional SC was formed by the interplay of price and trust (Segerstedt, Olofsson, Hartmann, & Caerteling, 2010). Usually, a power play and opposite 'forces' emerge in the decision-making for inter-organisational IT (Adriaanse et al., 2010a). There is a consensus that alliances and partnerships would require, among others, IT mechanisms, underpinned by legal and contractual frameworks, to support their operations and collaboration (Dossick & Neff, 2010; Rezgui & Miles, 2010). The contemporary SC is formed not only as to price or quality but also as to BIM-readiness. BIM has become a "prerequisite in delivering integrated construction SC practice" (Mahamadu et al., 2014). BIM adoption shifts from being an external 'market' demand towards being an intra-organisational drive. In the cases, the firms sought equally BIM-skilled SC partners. In cases C and E, the contractors and clients apart from their traditional role to drive SC integration were committed to the adoption of BIM (see Table 12). Thus, BIM becomes a prerequisite for SC partnering, and accordingly, BIM could be considered a new type of IT for practitioners and firms that engage in SCM.

Due to the increased number of involved actors in BIM-based projects, their roles were found to transform, as previously suggested by Sebastian (2011b). Mäki and Kerosuo (2015) assessed that the changes in rules and division of labour among the project actors from BIM will induce "consequences in the network of other activities of construction". After all, Nederveen et al. (2010) previously noted that the suppliers could soon assume a more decisive role in the design process. Some unexpected findings of newly-amended roles of the actors, from BIM-enabled SC partnering, observed throughout the five cases, are:

- The clients requested BIM-based project delivery although it was not clear if BIM would be used for maintenance (cases A, B, D, E).
- The contractor was usually the BIM-coordinator and often offered the infrastructure (physical and digital) for BIM sessions (cases A, C, D, E). In case B, the architect was responsible for this function.
- The architects and structural engineers were BIM-proficient in all cases. The architects usually had the additional task to integrate building information from suppliers that were not using BIM (cases C, D, E).
- Some suppliers and sub-contractors also used BIM because of either internal or external demand (cases A, B, C, D).

§ 3.5.3 Research limitations and applicability

Given that the research was largely exploratory, not all the observed BIM collaboration patterns were manifested with the same frequency (see again Table 13). Further research with cases of BIM-enabled SC partnerships would be needed to validate the *ad-hoc* collaboration pattern, which was only present in case E (past project). The BIM collaboration patterns that emerged in this study – *ad-hoc, linear*, and *distributed* – may also pertain to non-SCM settings. The recruitment of these cases with BIM-enabled SC partnering was facilitated by the fact that the various actors were already organised in structured relations and their availability to share information for research purposes was collectively and unanimously decided. This collective decision suggests evidence against the arguments that construction SCM entails unilateral control on behalf of dominating firms (Fernie & Tennant, 2013, pp. 1041, 1054). Moreover, the promise of BIM to offer consistent information, through the IFC, aligns with the goal of SCM for consistent information flow. In the future, the SC partnerships or any project teams could be potentially benefited by *distributed* BIM collaboration patterns to achieve balanced inter-organisational collaboration.

The study goal was to explore the current status and interdependences of BIM and SCM. A research limitation was that for research proximity, all projects were located in the Netherlands. However, useful lessons and analogies could be extracted for other countries. The Dutch AEC is highly fragmented and diversified (Ozorovskaja et al., 2007; Bemelmans, Voordijk, Vos, & Buter, 2011). About 95% of AEC firms are micro-enterprises or Small-Medium Enterprises (SME) (EuropeanCommission, 2015). The results derived from the projects A and E could be more relevant to countries with larger construction companies (see Table 7). The observations from cases C and D could be more relevant to countries with chains of industrialised construction e.g. Finland; given that dry construction suppliers were internal SC partners in those cases. As BIM adoption is quite advanced in numerous countries (Succar & Kassem, 2015), yet not globally accepted, its combination with SCM practices could potentially further diffuse BIM. Likewise, BIM could be a vessel for popularising SCM and SC partnering that could, in turn, deliver higher performance consistency (Gosling et al., 2015). The SC partnerships could form a 'middle-out' strategy for BIM adoption.

§ 3.5.4 Further issues in BIM implementation

Undoubtedly, BIM has the potential to integrate the AEC lifecycle. Azhar (2011) claimed that among the challenges of BIM is finding the adequate time to include wisely the various actors in the process. Eadie et al. (2013) pointed out that BIM is usually mostly applied in the early stages and gradually less later. Here, BIM was mostly used in design management and construction (for logistics optimisation). BIM was used only sporadically during the initiation phase and the application areas associated with it (see Table 10). This 'late' adoption could be related either to the usually less BIM-ready project initiators, e.g. client and owner, or the fragmented AEC lifecycle during the permission stage that often causes delays. The SC actors of the cases B and C desired denser, better fine-tuned, and more informal interactions. BIM and SCM practices complemented each another and gradually overlapped. Nevertheless, this confirms that "BIM represents a new paradigm for AEC, one that encourages the integration of the roles of all stakeholders on a project" and that could promote greater harmony among the project actors (Azhar, 2011). Future research would be required to explore in greater depth the interdependences among actors, processes and the sharing of building product models.

§ 3.6 Conclusions

The contribution of this study lies in the analysis of BIM implementation in already structured inter-organisational settings. The observed *ad-hoc*, *linear*, and *distributed* BIM collaboration patterns entailed various forms of physical and digital interactions, quasi-contractual means and types of exchanged information. *Therefore, the interdependences between BIM technology and SCM philosophy in practice are found in a complex system of different types of contractual, processual, and informational resources* (answer to RQ#2). The three patterns could present implications for policy makers, considering that the existing BIM mandates focus on file exchanges and not explicitly on the processual, product-related, organisational complexities of BIM-based collaboration. At the same time, there is a lot of discussions in the UK about 'collaboration' with BIM (see again Figure 8), but not a lot of evidence on how BIM-based collaboration practically takes place. Accordingly the processual aspects of Table 13 could be components and practical recommendations to be potentially included in the various National 'BIM mandates'. These patterns could suggest the ingredients for guiding BIM implementation for construction managers.

The results have demonstrated a conceptual and practical link between BIM and SCM concepts. There has been limited research on BIM implementation from SC partnerships. The SCM practices of the partnerships could be supported by BIM implementation at a technical level and regulate the SC information flows, e.g. using clear BIM protocols. Simultaneously, the informal settings of SC partnering could facilitate the BIM implementation process by offering a more trusting environment for collaboration, e.g. using co-locations. Subsequently, BIM and SCM concepts were found practically highly interdependent throughout these three BIM collaboration patterns. This chapter could provide the ground to popularise further BIM adoption from a 'middle-out', i.e. inter-organisational, level with the ultimate goal to improve the exchanged products, complex processes, and inter-organisational relations in AEC.

4 Design of a BIM-based Supply Chain analysis tool[4]

Chapter summary

Following up on the previous exploration of the combination of SCM with BIM in an empirical setting (Chapter 3), this chapter revisited their grounded combination at a conceptual level. The previous findings on the transforming roles of the supply chain partners – or actors – suggested the need for a detailed analysis of the actors' interactions. The intention was to materialise the interdependences between SCM and BIM in a modelling framework that could be further applied to analyse more BIM-enabled SC partnerships and in particular their coordination mechanisms (RQ#3). Modelling was selected for being a compatible approach with both main constructs, i.e. SCM and BIM. After analysing various modelling approaches pertinent to the AEC industry, input from Organisational Networks and product modelling were used, following the conceptual framework of Process/Product/Actor (P/P/A), previously developed in Chapter 2.

The proposed analysis model consists of a combination of product models, in the form of the exchanged IFCs among the SC actors, processual information from the project timelines, and the organisational model of the involved actors in the SC partnership. The model uses quantitative data derived from the collation of the afore-described data, interviews, and document analysis of a real-world case with BIM implementation, and namely Case A from the pool of five cases in the previous empirical study. This case was selected as a scenario case for a proof-of-concept because it displayed a sophisticated BIM collaboration pattern, i.e. the 'distributed' pattern. The data are combined in a database, represented with network visualisation software, and analysed quantitatively. This application intended to showcase the capabilities of this analytical method. Among the findings are indications of processual mismatches among the interactions of the actors and organisational mismatches between the contractual and actual position of certain influential actors in the project. From the analysis of Case A, it was deduced that the BIM-enabled SC partnership displayed decentralised, rather than centralised control.

4 The sections § 4.2 and § 4.4 of this chapter are largely based on (a) a paper published in the European Conference on Product and Process Modelling (Papadonikolaki & Verbraeck, 2014), and (b) a paper published in the journal of Structural Survey (Papadonikolaki et al., 2015).

§ 4.1 Introduction

§ 4.1.1 Coordination in BIM-enabled SC partnerships

The AEC Supply Chain is currently more complex than ever and difficult to be coordinated, due to the large number of participants in the project (organisational complexity), fragmentation, and ramifications in the delivery (processual complexity), and technical challenges in construction projects (product-related complexity) (Winch, 2002). On the one hand, SCM philosophy aims to coordinate the flows of material, information, money, work crews, and capital equipment among a set of strategically aligned companies (Mentzer et al., 2001), by engaging them in transparent collaborations. On the other hand, BIM as a technology-driven approach offers benefits to both products and processes of AEC, by collecting and representing building project information, and hence supporting information sharing. In that sense, BIM is an integrative technology (Eastman et al., 2008). The accredited benefits of BIM include cost and time reduction, communication, negative risk reduction, scope clarification, coordination improvement, fewer software issues, fewer returns for information, and coordination improvement (Barlish & Sullivan, 2012; Bryde et al., 2013). Accordingly, potentially, BIM could have an impact on the coordination of the SC flows and play a role in the coordination of BIM-enabled groups of actors (Dossick & Neff, 2010; Merschbrock, 2012), and potentially also of BIM-enabled SC partnerships.

However, there are currently reports on changing dynamics in the roles of the actors induced by BIM (Arayici et al., 2011; Sebastian, 2011b). Presently, SCM applications in AEC are often process-oriented and do not include any integrated information management or look at the product-related aspects of the project. BIM could potential fill this gap. As presented during the real-world combination of SCM with BIM in the empirical explorations of Chapter 3, the BIM-based collaboration of a SC partnership is a complex process, which could manifest in various patterns of relations of processual, product-related, and actor-related nature (see again Table 11). To further analyse the collaboration in BIM-enabled SC partnerships, a glimpse into the concept of 'coordination' was introduced. Coordination entails the notion of 'order' and it aims to rationalise formal mechanisms of interaction among various actors. Whereas the two concepts of SCM and BIM were interdependent across various facets, this chapter will focus more on the former by using the latter as a supportive means for the analysis of BIM-enabled SC partnerships.

§ 4.1.2 The relation between Collaboration and Coordination

Mattessich and Monsey (1992) in their effort to define collaboration, also reviewed tangential concepts, such as cooperation and coordination. They held an inter-organisational perspective to define collaboration as a dynamic and:

"mutually beneficial and well-defined relationship entered into by two or more organisations to achieve common goals. The relationship includes a commitment to: a definition of mutual relationships and goals a jointly developed structure and shared responsibility; mutual authority and accountability for success; and sharing of resources and rewards" (Mattessich & Monsey, 1992).

This definition aligns to the afore-defined perspective on the SCM philosophy (see section § 2.3). To differentiate with the term 'coordination' they highlight that it is characterised by formal relationships, compatible missions, and the pre-requirement of planning, division of roles, and established communication channels (Mattessich & Monsey, 1992). For other researchers, 'collaboration' is a simpler term, which essentially describes people "working together on an intellectual endeavour" (Malone & Crowston, 1994), whereas coordination could be considered a 'higher involvement' collaboration.

In the context of 'creative industries', Olson et al. (1995) propose that for the coordination of cross-functional teams in creative environments, a spectrum of two opposing coordination mechanisms could be applicable. First, in projects that involve innovation, "organic, decentralised, and participative coordination mechanisms" could achieve better results, however, in routinised work, the centralised and formalised coordination structures would be more efficient (Olson et al., 1995), as shown in Figure 14. Structural attributes, such as the team complexity, distribution of authority, formalisation, and processual attributes, such as the decision-making process, information, and workflow predicate a spectrum of coordination mechanisms, from rigid hierarchies to 'organic' developments (Olson et al., 1995) (see Figure 14). Undoubtedly, the AEC industry can be considered a 'creative industry' as well. Therefore, as the design process of projects in AEC is inherently creative, but the engineering process could be probably routinised, a conscious alignment with either centralised or decentralised coordination mechanism is largely required.

Types of Coordination Mechanisms

Structural and process variables	Bureaucratic Control	Individual Liaisons	Temporary Task Forces	Integrating Managers	Matrix Structures	Design Teams	Design Centers
Structural Attributes							
Complexity	Simple structures	↔	↔	↔	↔	Complex structures	
Distribution of Authority	Centralized	↔	↔	↔	↔	Decentralized	
Formalization	High; More Rules	↔	↔	↔	↔	Low; Fewer Rules	
Unit Autonomy	Low	↔	↔	↔	↔	High	
Processes							
Decision Making	Hierarchical	↔	↔	↔	↔	Participative; Democratic	
Confict Resolution	Hierarchical	↔	↔	↔	↔	Participative; Consensual	
Information Flow	Vertical; Formal	↔	↔	↔	↔	Horizontal; Informal	
Work Flow, Job scheduling	Sequential	↔	↔	↔	↔	Concurrent	
Evaluation and Rewards	Based on Functional or Company outcomes	↔	↔	↔	↔	Based on Project or Unit outcomes	
Motivational Focus	Functional	↔	↔	↔	↔	Customer/Project	

FIGURE 14 Structural attributes and processes of various coordination mechanisms, adapted from Olson et al. (1995).

Across the literature, different definitions of collaboration and coordination could be found. For Malone and Crowston (1994) collaboration refers to actors “working together on an intellectual endeavour” and they advise that both collaboration and coordination could be considered as different approaches to managing dependencies among activities, i.e. coordinate those actors. For them, coordination is the management of tasks dependencies between activities, inter-disciplinary actors and resources (Malone & Crowston, 1994). Such coordination structures might even refer to the decision-making process in organisations or markets (Malone, 1987). This definition of coordination is consistent with the use of the concept of coordination from prominent researchers in the area of SCM. For example, for Mentzer et al. (2001) coordination pertains to the activities of the SC systems at a strategic and tactical level. For Lambert et al. (1996) SC coordination is an intermediate level of SCM among firms, which is a pre-requisite of true organisational integration, i.e. SC integration.

The objective of this chapter would be to identify the ‘coordination mechanisms’ of BIM-enabled SC partnerships as the main objective, e.g. identify whether these are centralised or decentralised, according to Olson’s et al. (1995) taxonomy, such as team complexity, distribution of control, information and workflow. To coordinate the design and engineering processes, the actors, resources, and tasks should be coordinated first, and to do so, the various ramifications should be understood, i.e. analysed. Subsequently, the coordination is seen as a means to support decision-making and potentially instigate closer collaboration. This chapter presents the development of a SC analysis model using heterogeneous data also from the BIM applications. The objective is to propose a method and create an analysis tool for BIM-enabled SC partnerships, utilising concepts from both SCM philosophy and BIM technology domains. The chapter focuses on the *RQ#3: How to combine the SCM with BIM concepts to analyse BIM-enabled SC partnerships?* Before answering this question, two other sub-questions will be considered:

- Why could modelling be an approach for the analysis of BIM-enabled SC partnerships? What has so far already been developed in this direction?
- What existing modelling approaches could contribute to the development of a BIM-based SC analysis tool? And how?

The following section (§ 4.2) describes the choice of using a modelling approach to develop a coordination analysis tool for BIM-enabled SC partnerships and presents a brief history of other modelling approaches in AEC and in general. Section § 4.3 presents some background on various types of modelling that contributed to the development of the proposed method. The proposed modelling framework and a scenario case as a proof-of-concept are presented in sections § 4.4 and § 4.5 respectively. A discussion from a socio-technical perspective (section § 4.6) and conclusions (section § 4.7) follow.

§ 4.2 Background

§ 4.2.1 Coordination in AEC, pertinent to SCM and BIM

The concepts of logistics, business organisation, and partnerships were adopted in SC research approximately in the mid-80s (London & Kenley, 2001) from the field of Operations and manufacturing. However, as the construction industry usually deals with unique products, the 'SC thinking' is not directly transferable to the context of AEC. The process and products variability and the irregular distribution of relations among the members of the AEC organisations are non-negligible aspects of this unique character (Towill, 2009). Whereas the building industry is crucial to capital markets and national economies, the AEC SC is loosely inter-related and, therefore, generally unreliable and inefficient. These phenomena result in a variety of losses, such as time delays, cost overruns, and quality issues. According to Azambuja and O' Brien (2009), responsible for this situation are the fragmentation of the industry in its constituent parts due to the lack of coordination among organisations, and lack of sharing accurate, controllable and integral information among the organisations. Hence, coordinating the information flows by evaluating possibilities of construction IT, e.g. BIM, could be a solution for the afore-described deficiencies. As this research focuses on inter-organisational chains, it would analyse the complexities in organisational operations and structure, i.e. the coordination of the design and engineering.

In the context of SCM, and attempting to shed light on the definition of SC coordination, Kanda and Deshmukh (2008) conclude that coordination in the SC could take place in the areas of logistics, inventory, forecasting, and product design. SC coordination has been focusing on coordinating the inventory management – of usually a focal firm –, the contractual relations, and the information sharing with the aim to tackle uncertainties in the manufacturing process, assembly, and distribution (Chan & Chan, 2010). For example, Vendor-Managed Inventory (VMI) approaches of a focal SC firm attempt to minimise the inventories and the delivery times (Cheung & Lee, 2002). Another initiative to coordinate the SC is through the Supply Chain Operations References (SCOR) model, which has been developed by the Supply Chain Council, an industry consortium, and aims to create a common language for strategic deployment of SCM among top managers (Huan, Sheoran, & Wang, 2004). Collaborative Planning, Forecasting and Replenishment (CPFR) is a set of guidelines, initiated by Wal-Mart that aims to coordinate numerous activities, such as forecasts and replenishment, among two or more companies (Seifert, 2003). Naturally, in all these afore-described SC coordination initiatives, various coordination mechanisms could be applicable, such as contractual means, IT, information sharing, and joint decision-making (Kanda & Deshmukh, 2008). The various SC constellations could be, thus, inter-connected through relations such as resources, contracts, and communications' synchronisation.

Many analytical approaches to SC coordination focus on 'focal firms' or 'dyadic' supply chains (Chan & Chan, 2010), and whereas these approaches would be largely efficient to find the optimal solution in isolated problems, they present the drawback of being disconnected and quite inflexible for the real-world uncertain – highly networked – environment. On the contrary, when considering the SC configuration as a decentralised system, its analysis might be more complicated, but the insights into the dependencies among the actors, the available resources, and the time constraints could be much richer. Essentially, between SC hierarchies – such as 'focal firms' or 'dyadic' SCs – and SC networks, the latter could emulate a dynamic network behaviour, close to the complex behaviour of the numerous inter-related SC partners. This behaviour could be explored through various parameters, as presented above, such as contracts, power relations, information sharing, resources, and trust.

In the context of BIM, collaboration might not necessarily entail shared goals, responsibility, resources, and risks, but could be related more to the afore-described concepts of collaboration, i.e. 'mutually design authority' and essentially people working together (Mattessich & Monsey, 1992). For example, in relation to BIM, the term 'coordination' is often used to describe the process of 'design coordination' and in particular as BIM coordination sessions, e.g. for clash detection (Cidik et al., 2014), which raises issues of design ownership and control. With regard to the inter-organisational relations among MEP engineers, Dossick and Neff (2010) conclude that with BIM there is not only a need for better-structured teams, but also a need for increased leadership of engineers and managers to encourage closer collaboration among project participants. In other words, Dossick and Neff (2010) advocated the need for control and order to coordinate the collaboration process with BIM. Similarly, Merschbrock describes the BIM design coordination process as an 'un-orchestrated symphony' (2012), where the various actors work on 'automation islands' by carrying obsolete collaboration patterns from their past experiences. In principle, BIM collaboration among a virtual network is a complex process that hinders coordination due to the geographical disparity of its members, unbalanced team configuration, and incongruent team interests (Mignone et al., 2016). Therefore, it has already been acknowledged that the BIM coordination process is materialised in 'organic' networks, beyond any hierarchical prescriptions, such as legal, contractual, or business-related.

From the above, we could conclude that there are two different notions of coordination pertinent to SCM and BIM respectively. Coordination pertains to the SC coordination among firms to achieve a project goal and SC integration, but also to the day-to-day (design) coordination with BIM. Therefore, SCM and BIM have different UoA regarding the concept of 'coordination'. In the context of this thesis, the SC coordination pertains to the actors, but at an operational level and not from the perspective of strategic purchasing, competition, and alignment. The concept of coordination could be used for increasing the understanding of the complex and multi-faceted BIM collaboration patterns of Chapter 3, regarding the processual, product-related, and organisational aspects. Between the hierarchical and networked structures, which were presented above, this research adopts the network-type structure, as this presents greater affinity to the emerging BIM-based collaboration patterns, and thus, could be considered their common ground. About the various inter-organisational parameters that could play a role in the coordination of the BIM-enabled SC partnerships, the information flows and the contractual relations resonate more with the BIM and SCM concepts respectively.

§ 4.2.2 Rationale for a Modelling and Simulation approach

From the above, the analysis of the coordination process in BIM-enabled SC partnerships could form the path for managing both the SCs and the BIM (collaborative) process. After all, coordination is a common concept to both BIM and SCM fields. Basically, to manage is to engage in a complex decision-making process that is grounded on various types of analyses. For example, for Malone and Crowston (1994) to coordinate multi-functional or inter-disciplinary roles, one should manage the task dependencies by analysing their common activities, actors' relations, and shared resources. On 'analysis', Malone (1987) had previously suggested that:

"models can be used to (a) help understand major changes that have occurred in the structure of American businesses during the last century, (b) make speculative predictions about the possible consequences that the widespread use of information

technology may have for organizational structures, and (c) help analyse and predict design options for computer processing networks."

A model is an abstractive representation of a physical or conceptual system. According to Kaplan, (1973) "any system A is a model of a system B if the study of A is useful for the understanding of B without regard to any direct or indirect causal connection between A and B." Modelling and Simulation (M&S) is an analytical approach that could be used to represent the phenomenon under study, i.e. the BIM-enabled SC partnerships, and analyse them to propose improvements to their structure. Modelling offers quantitative analyses, in which the real system is abstracted for either description or analysis. Simulation is the executable version of this model over time. The manner in which time is conceptualised in the simulation predicates different types of simulation, i.e. formalisms. M&S could analyse the system in question, e.g. a supply chain, and offer operational insights (Law & Kelton, 2000). Since the combination of BIM technology and SCM philosophy is not formally established or previously conceptualised, an experimental approach using M&S was selected.

M&S could be considered a common approach to both BIM and SCM concepts. On the one hand, the native file format of BIM, i.e. IFC, is represented in EXPRESS-G, the graphical representation of the EXPRESS modelling language. After all, BIM was initially introduced as Building Product Model (BPM) – a less articulate acronym than BIM – and it is based on product models (Eastman, 1999). On the other hand, modelling is among the five main approaches to SC research, the others being: theory building, surveys, case study research, action research (Seuring, Müller, Reiner, & Kotzab, 2005). Thus, modelling could be a compatible method for analysing and potentially supporting the BIM-enabled SC partnerships. Throughout simulation studies, there are many approaches to representing the structure of a SC: 'serial', 'dyadic', tree-like', and 'network-type' structures (Chan & Chan, 2010). From those, this study focuses on a 'network-type' for modelling the phenomenon of BIM-enabled SC partnerships (see again Figure 5).

§ 4.2.3 Review of Modelling and Simulation approaches in AEC[5]

History of Modelling and Simulation

The developments in the field of simulations coincide with the first programming "language efforts" between the years 1955 and 1960 (Nance, 1995). Since then, many

5 This sub-section is largely based on a paper published in the European Conference on Product and Process Modelling (Papadonikolaki & Verbraeck, 2014).

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general purpose simulation systems and special purpose languages were created, configured and used to now. The theory of M&S has its roots in Systems Theory. A system contains essential parts or sub-systems with their own indigenous behaviours and properties that constitute a functional whole for a specific purpose (Ackoff & Gharajedaghi, 2003). To analyse a system one constructs a conceptual model, which is – de facto – an abstraction of the reality (Richmond, 2003). For Shannon (1975) the simulation is the process, or 'art', of designing a model of a real system and conducting experiments to either understand the behaviour of the system or evaluate various 'what-if' scenarios about it.

The complexity of the conceptual model should be proportional to the real complexity of the system (Ackoff & Gharajedaghi, 2003), so as not to over-simplify and compromise its complexity, which in turn could result in system failure. The reality is represented as either static or dynamic models (Law & Kelton, 2000). Static models are useful in representing the structure of the system, such as the E-R models, spreadsheet models, and Monte-Carlo simulations, which are based on the generation of random numbers. Dynamic models represent the change of an existing state and make calculations and predictions, by using time as an "indexing attribute" (Nance, 1981). Therefore, between static and dynamic models, the latter could offer greater understanding in a coordination process, which as mentioned above, essentially incorporates the notions of 'order', 'control', and 'time.'

Modelling and Simulation studies in AEC

The emergence of simulation research in construction industry began in the mid-60s. Numerous researchers used the developments in the field of M&S to simulate construction operations. Table 14 summarises some key developments in this area. Most of these developments are research products of PhD theses, e.g. the developments of the researchers Carr, Liu, Odeh, and Martinez, described in Table 14, and mainly used general purpose simulation languages. From 1996 and onwards, the simulation initiatives also included the use of special simulation languages. This variety of developments is likely derived from the polyphony of the worldview, definitions, approaches, and time-related formalisms. A similar redundancy and polyphony had taken place during the development of simulation programming languages (Nance, 1995). Apart from the variety of means and languages, there is also a variety of research objectives and research foci. Some of the developments are more operational and managerial, while others adopt a more technical – or engineering – approach to the problem at hand.

TABLE 14 Development of simulation systems in the construction industry.

YEAR	RESEARCHER(S)	PRODUCT	TYPE
1963	P. M. Teicholz	"link-node"	-
1970	A. Pritsker & R. Burgess	GERT networks	-
1974	D. W. Halpin	CYCLONE	G*
1980	A. Kalk	INSIGHT	G
1981	D. W. Halpin	MicroCYCLONE	G
1986	Chang	RESQUE	G
1989	R. I. Carr & P. G. Ioannou	UM-CYCLONE	G
1991	L. Y. Liu & P. G. Ioannou	COOPS	G
1993	D. F. McCahill & L. E. Bernold	STEPS	G
1994	A. M. Odeh	CIPROS	G
1995	R. Y. Haung & D. W. Halpin	DISCO	G
1996	J. C. Martinez	STROBOSCOPE	G
1996	J. C. Martinez	EZStrobe	G
1996	AbouRizk & Hajjar	AP2-Earth	S**
1997	K. J. Kim & G. E. Gibson	KMOS	G
1998	J. C. Martinez	EarthMover	S
1998	Hajjar & AbouRizk	CRUISER	S
1999	AbouRizk & Hajjar	Simphony	S
1999	J. J. Shi	ABC	G
2000	A. Sawhney & H.t Despande	Java-Based	S
2002	D. K. H. Chua and G. M. Li	RISIM	S
2003	Marzouk & Moselhi	SimEarth	S
2003	M. Lu	SDESA	-
2009	AbouRizk & Hague	COSYE	S
2010	D. -E. Lee, Yi, Lim & Arditi	COPS	-

*G: General-purpose simulation language, **S: Special-purpose simulation language

The developments of simulations research in construction presented in Table 14 could be roughly divided into two generations. The first generation is up to 1996 and focuses primarily on construction operations and management. The second generation is from 1996 onwards where there is a provision for more complex problems and extensibility towards SC research (Martinez, 2001). Meanwhile, some developments from 1993 included certain principles of object-orientation combined with the Discrete Event simulation models (Oloufa, 1993; AbouRizk & Hague, 2009). Object-based development includes principles of encapsulation, polymorphism or inheritance, which consequently facilitate hierarchical modelling and could achieve modularity in a model design (Eastman, 1999). Modularity and extensibility are essential for modelling complex systems such as supply chains.

Observations on the existing M&S approaches in AEC

Most of the literature on simulation of construction SCs refers to the simulation of real-world cases for earth moving operations, concrete floor pouring operations, flows of crew movement, road paving processes, earth hauling, and truck moving operations. From a review of the scientific literature (n=86) on modelling and simulation research on construction supply chains, it was found that those focus more on the modelling and simulation of the 'behaviour' of material and equipment entities on the construction site (Papadonikolaki & Verbraeck, 2014). In Table 15, these modelling and simulation studies have been sorted under increasing organisational complexity of their 'real' systems: from construction site operations to intra-organisational level and then to inter-organisational level (from top to down in the titles of the rows). Furthermore, the simulation models have been sorted under increasing complexity of the simulated flows: material, equipment, workforce, information and combinations of flows (from left to right in the column headings). From Table 15, one would normally expect that the level of complexity of the simulated flow would have been proportional to the level of the actual organisational complexity in the research. While information exchanges are critical to inter-organisational supply chains, these flows are neglected throughout the relevant research.

TABLE 15 Association between the modelled SC system type and the chosen simulated entity in the literature (n=86).

CONSTRUCTION SC TYPE	MATERIAL	EQUIPMENT	ACTORS	INFORMATION	MATTER & INFO	ALL FLOWS	TOTALS
Construction Operations	11	13	0	2	0	4	30
Intra-organisational	7	2	3	1	2	4	19
Inter-organisational	13	5	4	5	2	3	32

The research focus of simulation studies for construction SCs is primarily on construction site operations and inter-organisational chains. Currently, the emphasis is placed on specific components of the construction SC, such as material and equipment (see Table 15). The research of the chain at an intra-organisational level also was not very popular across this research sample. At an intra-organisational level, the research lacks the simulation of information flows among its involved actors. The present scientific literature has been focusing on the improvement of specific parts of the SC, such as of the construction site operations. However, "when the performance of any essential part of a system, taken separately, is improved, the performance of the whole may not be" (Ackoff & Gharajedaghi, 2003), which would mean that by isolating the research problem on construction site operations would not necessary untangle all the ramifications of construction projects and chains. Simulations of the information flow are also not very popular in AEC (see Table 15). At the same time, the informational exchanges cannot be modelled without taking into consideration the interaction among the SC actors, for the purpose of coordinating their tasks.

This imbalance between conceptual modelling and practical implementation of the simulation studies results to inefficient and hard to generalise simulation applications in AEC SCs. To deal with this imbalance, a modelling approach could focus more on inclusive representations of the AEC SC system, and particularly with the organisational level of SC research meeting the appropriate complexity level of the simulated entity, i.e. focus on information flows. In general, a shift towards the simulation of information flows for every level of organisational focus of the SCs could support a complete representation and understanding of the construction SC systems. The flows of information between the project actors have been neglected in both intra- and inter-organisational chains. Hence, for a balanced approach, a focus on the modelling of the information flows could support the disentanglement and potentially improvement of the fragmented image of construction SCs. Probably, the complex AEC SC requires a special research approach, to correspond to all the product-related, processual, and organisational complexities described in Chapter 2. Likewise, the level of complexity in the modelled entities of an AEC SC system should be proportional to the complexity of the real system and the research objectives. Since the AEC SC is a complex multi-faceted system, it could then be represented using a combination of models. This study proposes the combination of product, process, and organisational models to analyse BIM-enabled SC partnerships.

§ 4.3 Existing Modelling approaches

§ 4.3.1 Graph-based models

Graphs are popular tools for representing complex models, by virtue of their modelling flexibility that further offers an intuitive and creative modelling environment. Graph Theory has numerous applications in computer science, electrical engineering, and operations research. The basic module of a graph is a triple that consists of two nodes (or vertices), connected through an edge (line or arrow). Graphs are also popular in BIM research since the IFC is usually represented as a hierarchical data model i.e., in EXPRESS-G, the graphical representation of the EXPRESS modelling language. Moreover, graphs are very popular in portraying SCM concepts, e.g. block diagrams of the relations among the SC actors, e.g. in Lambert et al. (1998) (see Figure 15), O'Brien et al. (2002) and London (2009). In Figure 15, Lambert et al. (1998) have represented a focal firm and at least three tiers of their suppliers and customers as a tree-based (hierarchical) graph consisting of nodes (other firms) and lines (purchasing relations). In Figure 16, Pryke (Pryke, 2012) represented the AEC supply chain as a non-hierarchical network, where the various actors exchange information beyond their contractual relations. Thus, graph-based approaches have already provided powerful visual and analytic tools for representing SC complex systems, either hierarchical or of network-type.

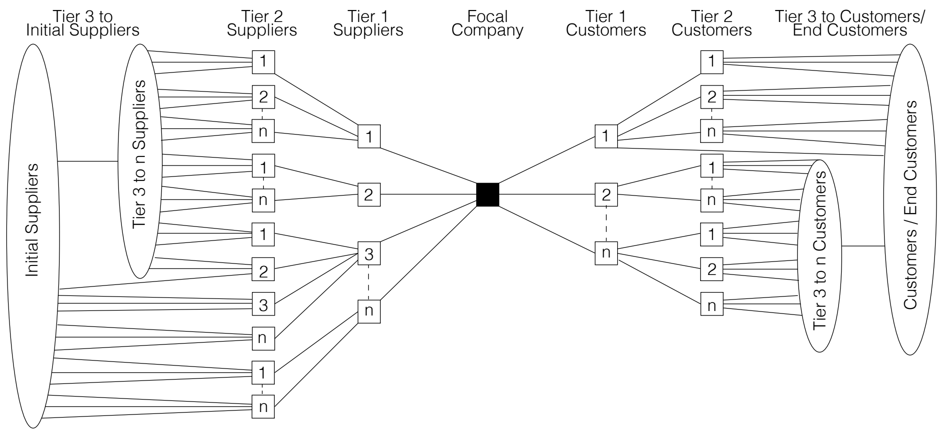

FIGURE 15 Typical representation of a Supply Chain Network Structure (adapted from Lambert et al. [1998]).

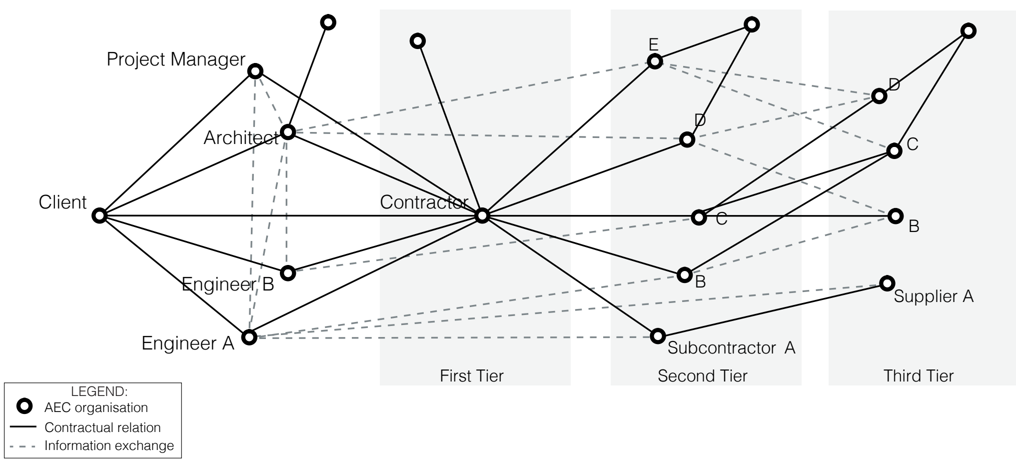

FIGURE 16 The AEC supply chain network (adapted from Pryke (2012, p. 2)).

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Graph Theory has its roots in the 17th century when a topological puzzle – the bridges of Koningsberg – attracted the interest of Euler, who used mathematics to resolve the problem (Biggs, Lloyd, & Wilson, 1976). Since then, graphs have become natural in systems theory, software engineering, and computer science. While in OR and SCM research, graph-based approaches are popular for some decades now; they have only recently been introduced to BIM research. Graph-based methods are used in BIM applications to map topological, i.e. physical, relations within buildings or to clarify the actors' configuration. Besides representing product-related aspects, graph-based models are used in rationalising more intangible process- and actor-related aspects of the AEC. Merschbrock (2012) created a network of collaborating actors and identifies the architect as a communication hub. BIM and graph theory have been combined for change management in construction (Isaac & Navon, 2013). Hickethier et al. (2013) analysed the BIM-based interaction of various actors in an IPD project using graphs. From the above, the graphs could be quite eloquent for the representation and understanding of socio-technical systems, and particularly of inter-organisational BIM use. However, in BIM research the graphs are more likely to be used to represent the groups of actors are networks, rather than hierarchies, which has been customary in the SC research.

§ 4.3.2 Modelling types

Product and process modelling

A product model is a set of specification data for a given artefact – physical or conceptual. The need to formalise and structure these data in a logical way so as to represent knowledge generated the area of data modelling (Eastman, 1999). In AEC, the need to achieve a high-level definition of the building systems generated the area of product modelling by using the advancements in data modelling (Dado et al., 2010). A popular type of data model is the E-R model, where information is defined regarding entity, relation, and attribute. Within construction, the IFC model is an industry standard definition of products and processes, used for data modelling and interoperability in many proprietary applications. But, since essentially it is an E-R model, it lacks the notions of time, and it faces a "process and data dependency problem" (Eastman, 1999). The product models can also be represented as either hierarchical, i.e. tree-like or Product Breakdown Structure (PBS), or network-type models. A Work Breakdown Structure (WBS) follows again a similar logic to the PBS to hierarchically represent relations among project fragments. However, in network-type product models, the inheritance property allows for multiple 'child-parent' relations, and therefore is closer to representing complex real-world systems.

Business Process Modelling, or simply process modelling, represents the activities within one organisation. Process Modelling produces a 'blueprint' of order and work breakdown structure. Similarly to any model, these models could also be either static or dynamic (Law & Kelton, 2000). Static models simply represent the structure of the system. For instance, Business Process Modelling Notation (BPMN) is a static model, which has no state change or timing mechanism, although it has the notion of order and control. The dynamic models represent the change of an existing state throughout time. State machines, stock and flow diagrams, activity diagrams, and event graphs represent processes dynamically. Time is the indexing attribute that provides order and sequence. There exists no unified methodological framework for process modelling, regardless the research domain and goals (Reiner, 2005). Hierarchical and network-type models also apply to process models. For example, the Critical Path Method (CPM) is a network-type approach for process planning and avoidance of bottlenecks, which however requires highly detailed a priori knowledge of the duration of the involved activities. Case handling is another approach for representing processes via a network of work items and roles without separating on control points (Aalst, Stoffele, & Wamelink, 2003). Thus, it would be probably not sufficient to represent and coordinate all the intricacies of a complex system, such as the AEC SC, only via product and process models.

Organisational Models

Usually, project planning in AEC is tinted by considerations about the products and processes. However, from the above, the process and product models alone apparently cannot fully represent the AEC SC complexity, because they omit the input from the various multi-disciplinary actors. For example, in a BIM-enabled SC partnership, the BIM actors are non-negligible since with their intra- and inter-organisational behaviour, they influence both the products and processes. The SC actors could be represented in a 'Breakdown Structure', as in the PBS and WBS models, but this would entail an a priori rigid hierarchy and not dynamic network-type behaviour, which might nevertheless be more complicated but undoubtedly closer to reality. These actors exchange information in an iterative and bidirectional manner, beyond simple dual relations. Therefore, probably the actors of the BIM-enabled SC partnerships would be better represented as a network-type, rather than a hierarchical model (compare again Figure 15 with Figure 16). Besides, the interweaving relationships in such organisational networks cannot be represented on a bilateral basis (Kornelius & Wamelink, 1998). Moreover, the numerous organisations involved in a SC system increase its unpredictability and complexity. Therefore, analysing the actors involved in the SC systems could offer an additional level of analysis that could contribute to the decision-making and the structuring of the coordination processes in BIM-enabled SC partnerships.

Organisational models are usually illustrated as graphs or networks. Network Theory, as a subset of graph theory, is applied in many other contexts, from social sciences and operation research to medicine and epidemiology. Networks can represent the relations (lines, arrows or edges) among organisations (vertices, posts or nodes) (see again Figure 15). At a high-level, AEC is considered a loosely-coupled network of numerous organisations that temporarily coordinate within and for projects (Dubois & Gadde, 2002a). These high-level – or strategic – networks are responsible for establishing long-term communication, trust, and commitment. Pryke (2004, 2005) creates organisational models – which he calls Social Network Analysis (SNA) in construction – to visualise and analyse information exchanges, performance incentives, and contractual relationships and concludes with the deployment of network metrics for project governance. At an operational level, Farshchi and Brown (2011) perform SNA to measure the employees' information exchanges and define the knowledge and culture transfer within project-based teams. Accordingly, graphs could explain the organisational complexities of an AEC SC system in various scales, e.g. industry, organisations, and employee). However, as mentioned previously in section § 4.2, there are two different levels that coordination of BIM-enabled SC partnerships could be studied. These levels pertain to a strategic level for the SCM philosophy, and to an operational level for BIM respectively. This study focuses on the inter-organisational relations from a network perspective and at an operational level to gain insights into the coordination process and inform, afterwards, the strategic level accordingly.

§ 4.4 Modelling framework[6]

§ 4.4.1 Concept

The proposed SC analysis model aims at dealing with the afore-described multi-faceted complexity and analysing the coordination mechanisms in BIM-enabled SC partnerships. Usually, a representation of the product models, e.g. BIM, has little or no connections to a process schema. The processual information is what provides the notion of control and could thus clarify the emerging coordination mechanisms. In the majority of computer-aided business fields, e.g. Computer-Aided Design in AEC, the data – or product – model combined with the process model, produces the business model (Smith & Sarfaty, 1993). Therefore, the product model and the process model could produce the business model of an organisation. However, given that a SC involves

6 This section is largely based on a paper published in the journal of Structural Survey (Papadonikolaki et al., 2015).

various organisations, the combination of product and process modelling alone is not sufficient to describe the complexity of the inter-organisational system. As also deduced from the theoretical framework (P/P/A) of Chapter 2, a focus on processual, product-related, and actor-related considerations, could describe the current challenges in the AEC SC. Since the project team composition evolves over the different phases, the organisational model would also be dynamic.

The proposed model aims to represent the design and engineering coordination process and potentially support the decision-making accordingly by identifying mismatches and bottlenecks with regard to the product-related, processual, and organisational aspects of the BIM-enabled SC partnerships. The proposed synthesis is a merging between business models and organisational models by combining BIM-based product models with SCM philosophy in one graph. Following the network logic, which was described in the previous sections (see sections § 4.2 and § 4.3), various discrete entities of product, process, and organisational models are combined in an E-R model. The parameters of the organisational model pertain to contractual relations, such as information about both the internal, i.e. the strategic, and the external SC partners, given that the contractual relations are essential for the establishment of SC partnerships, as presented in section § 2.3. From the array of potential relations among organisational actors, which were previously discussed in section § 4.2, such as knowledge, trust, and power, the developed model will focus mainly on contractual relations and information exchanges (see also Figure 16), as these are more tangible parameters and the respective data can be collected more accurately. However, given that the model has been developed as an E-R model, potentially more parameters could be added in the future. This synthesis of heterogeneous models aims at being an "as-is" model to analyse, explain, and potentially improve projects with BIM-enabled SC partnering. It could be used to analyse product-, process-related, and organisational complexities in BIM-enabled projects. The rest of section § 4.4 presents the model and section § 4.5 the model application in a scenario case as a proof-of-concept.

§ 4.4.2 Development

The proposed modelling method aimed at analysing the complexity of coordination in BIM-enabled SC partnerships. It analysed the phenomenon into product-related, processual, and organisational entities and subsequently synthesised them in a graph-based model. The model analysed the system and produced an array of dynamic insights. Knowledge from both domains BIM and SCM research was used to design the proposed model, such as the afore-mentioned contractual relations and information flows. To guarantee its usability, the theoretical input from the modelling rationale was combined with input from practice. Before applying the model to real-world cases, three guiding model design requirements were set to ensure compliance with the research goals. Modelling requirements, adapted from Robinson (2006), guided the model development and assessment:

- The model should be applicable to various projects;
- The model should incorporate a consistent information flow, e.g. from BIM applications;
- The model should produce quantitative output for further analysis.

To develop a proof-of-concept of the proposed model, data from a scenario case were used. The data were collected from three main sources: the product, process, and organisational models. First, data were harvested from the product model as IFC files, used in the BIM applications. These were analysed with IFC File Analyzer, developed by the National Institute of Standards and Technology (NIST) agency of the USA Department of Commerce (Lipman, 2011). Second, the model used data from the process model of the project in the form of Gantt charts or spreadsheets. Third, the model used information about the degree of involvement of the various actors in the project, i.e. whether they were internal (strategic) or external SC partners. These three information sources were combined together in one database. The schema of these heterogeneous data sources is included in Appendix B (see Table 42, Table 43, and Table 44).

The graph-based model was produced with *Gephi*, which offers a visual and dynamic representation. Gephi is an open-source interactive visualisation and exploration platform for networks, complex systems, dynamic and hierarchical graphs (Bastian, Heymann, & Jacomy, 2009). It has a graphical user interface and a database environment and further enables data import and export in tabular file formats, e.g. databases, spreadsheets. There exist two tables in the tabular environment of Gephi: (a) one for the nodes (entities) and (b) one for the relations among those entities (see the previous discussions about E-R models). The IFC files were imported as spreadsheets, produced from the IFC File Analyzer, to Gephi. The various models were combined in Gephi by establishing their relations (edges). This process was semi-automatic since the filtering and import of the various models were automatic and their relations were created manually. A sample of the modelled nodes and edges from Gephi is shown in Appendix B (see Table 45 and Table 46). Then, the data from Gephi was inserted into the R programming environment for further statistical analysis and processing with code written in R programming language (RCoreTeam, 2013). The R script (code) that was used in the analysis of the afore-described data sources for the generation of the visual analysis in diagrams is included in Appendix B. The whole modelling process is documented in Figure 17.

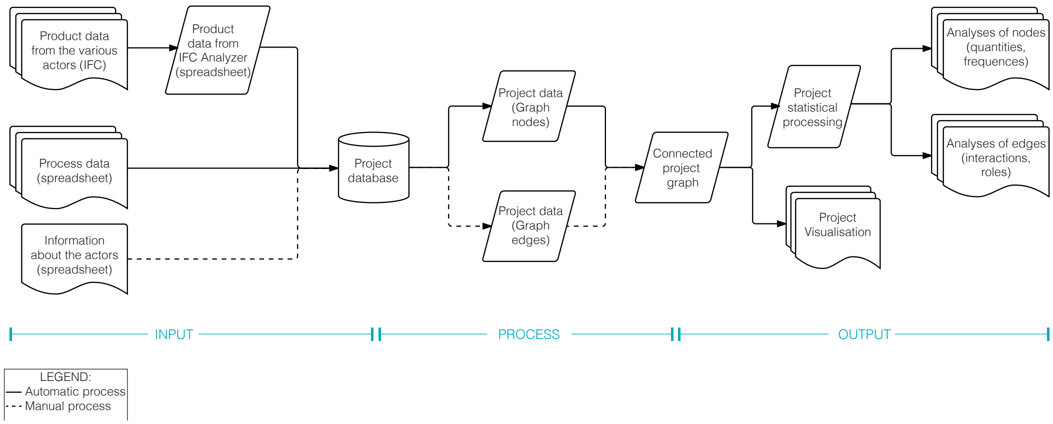

FIGURE 17 The combination of information sources for the generation of the analysis model.

§ 4.4.3 Module

The building block of the model is shown in Figure 18a. This module is an abstract fragment of the whole graph-based model. Figure 18a shows a simplified version of the product nodes (white nodes, Figure 18a, top). The model is illustrated as hierarchical, although it is a network, for readability. The product model is an E-R diagram that offers information only about the content and structure of the product, neglecting time sequence or organisational interactions. Process nodes (green node, Figure 18a, centre) are used to join the product model, i.e. the information from BIM sources, with the organisational model, or actor nodes (blue nodes, Figure 18a, bottom). These three entities follow the P/P/A components of the theoretical framework of Chapter 2 and stand for the processual, product-related, and actor-related features of a BIM-enabled SC partnership. By analysing the interactions among these types of entities, the proposed model will analyse the processual, product-related, and actor-related challenges respectively.

The afore-described entities are connected with two types of relations, which resonate with the previous discussions (see section § 4.2) about the possible relations among organisational models that could play a role in the analysis of the coordination in BIM-enabled SC partnerships. Accordingly, contractual relations and information exchanges were included in this model. The process nodes of Figure 18a carried the processual information from the project data, represented time, order, and sequence, and acted as the interfaces between the products and the actors. Each process had a pair of input-output (I/O) relations, which essentially was the product models produced per phase. Therefore, the I/O relations between the process and product nodes represented the 'action' of the information exchange.

Additionally, the process nodes were linked to the organisational entities of the model. The directional edges that connect the actors to the processes represented the 'interaction' of the information exchanges among the actors and their respective roles. The roles were adopted from transaction theory, such as initiator, enabler, and executor (Barjis, 2009), and were used to provide a notion of 'control' for the analysis of the coordination structure in the BIM-enabled SC partnerships. Figure 18b depicts an abstract higher-level structure of the proposed model. The resulted model is a combination of the product-, process-, and organisational models. As the model gradually evolves in time, the model was dynamic.

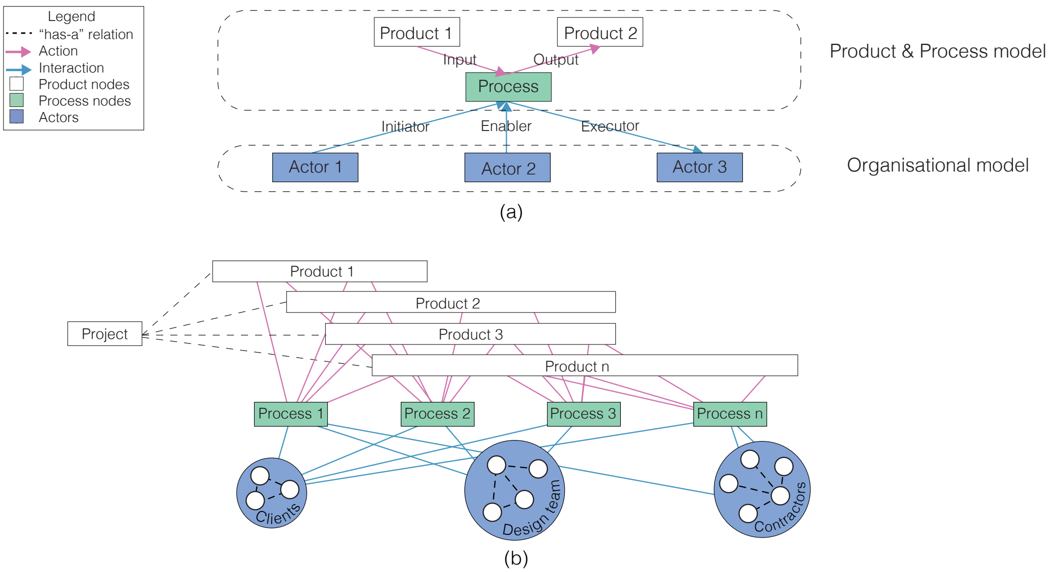

FIGURE 18 (a) The building block of the graph-based model, and (b) the high-level representation in a project context.

§ 4.5 Proof-of-concept

§ 4.5.1 Case description

After the presentation of the concept model for the analysis of BIM-enabled SC partnerships, a case was analysed as a proof-of-concept. The objective of this proof-of-concept was two-fold: (a) to showcase the operation and the features of the proposed model, and (b) to analyse a case of a BIM-enabled SC partnership and potentially provide an understanding of its coordination structure. First, the case will be used as a proof-of-concept to provide real-world data for the deployment of the model. Second, the case will be analysed to generate some insights into of the processual, product-related, and organisational complexities of the BIM-enabled SC partnership, which would otherwise had been hard to obtain using the methods deployed in Chapter 3.

For the proof-of-concept, a scenario case of an ongoing real-world case of a BIM-enabled SC partnership was used. Currently, the real-world combination of SCM philosophy with BIM implementation is quite rare in practice. The case project was selected from the pool of five real-world cases presented in the empirical analysis of Chapter 3, and namely Case A. It is a large scale and complex project and has a diverse design and engineering multi-disciplinary team. Therefore, it would be insightful for the exploration of the emerging coordination mechanisms of the SC partnership. Also, the project had several technical risks, e.g. building height, and the fact that its logistics are confined, due to the plot being adjacent to a canal. It is new construction of a multi-functional complex of 255 apartments, offices and shops, divided into three buildings and surrounded by public spaces. The building complex has special energy requirements, as to the incorporation of renewable energy sources, e.g. geothermal and solar, and accordingly, various actors are in play. Since it is a still ongoing project, only the initial phases were represented and analysed with the proposed model. This project was also selected, because it is a mature and "linked" SC, according to Lockamy III and McCormack's taxonomy (2004). Another non-negligible reason for selecting this case was the openness of the case participants and the availability of information for research purposes.

The project is located in Utrecht, Netherlands and consists of ten SC partners: client, contractor, architect, structural engineer, facility manager, energy adviser, and four engineering and installation firms (HVAC). The architect and heating installation firm are new actors and external to the SC partnership. The project is characterised by an integrated contract for maintenance of the building facility for 20 years. This contract presupposes some cultural alignment among the internal – or strategic – actors of the SC, as well as ensures knowledge transfer to a potential future collaboration. The rest of the partners have worked together on three other projects, one of which was BIM-enabled. The project SC is well defined but not yet integrated. They issued their joint BIM protocol early at the beginning of the project and held fortnightly BIM meetings for collaboration and informal weekly BIM sessions for training among the SC partnership.

The strategic – or internal – SC partners of the case are the client, the contractor, and two installation companies. This team composition is considered representative given that the client and the contractor are usually the main drivers of SC integration (Ling, Toh, Kumaraswamy, & Wong, 2014). The contractor is additionally linked with separate long-term partnerships with a structural engineer, with whom they have numerous previous collaborations, and another installation company. The weakest relation among the SC partnership is the architect. The architectural firm is a new partner for all the other actors and was hired after a competition. The technological investment of the SC partnership has emanated from the initiatives of the contractor, who hosts co-location meetings for the partnership and also maintains and updates the digital collaboration infrastructure, i.e. the Common Data Environment (CDE). No time or cost overruns have been so far observed at the project.

§ 4.5.2 Case analysis

As stated previously in the case description, the case will be analysed to generate some insights into of the processual, product-related, and organisational complexities of the selected BIM-enabled SC partnership. As the P/P/A framework, generated in Chapter 2, predicated the various complexities of the BIM-enabled SC Partnership, the processual, product-related, and organisational dimensions of the project will be analysed and associated through the developed modelling tool. To analyse this case with the model, the data were collected from three types of case documents: (a) contracts, to represent the contractual relations among the actors of the BIM-enabled SC partnership, (b) IFC files, to represent the product-related attributes of the project, and (c) project timelines, to represent the processual attributes of the project. Any additional information was obtained from unstructured and on-demand interviews with the case participants and data collection.

From the three building volumes in the complex, the analysis of only one volume was modelled, given that the building project was developed sequentially and not concurrently, and there were different timelines for each volume. From the three volumes, the one that contained the installation of solar energy collectors was selected, given that more actors would be active then. For readability, the network of the BIM-enabled SC partnership has been presented as a hierarchy in Figure 19. Figure 19 is essentially an instance of the model in Figure 18 for the particular case of BIM-enabled SC partnership. Additional snapshots of the network of the modelled case – per phase – are included in Appendix B (see Figure 37). The modelled overview of the case is shown in Figure 19. It contains all the actions and interactions of the modelling entities and illustrates the project complexity. This representation in Figure 19 contains the interactions over time that took place during the deployment of the model. The product model is presented as a list of IFC entities on the top. The process model is the array of green nodes in the middle, and the actors are the set of blue nodes below. With a dashed line, the internal SC partners are represented (see Figure 19). The links – or relations – among the different models, are represented as arrows. The links between the product and the process nodes are input, means or output (pink colour). The relations between the process and actor nodes have notations from Transaction Theory, e.g. initiator, enabler, and executor (blue colour). Since the case is ongoing, the last phases are not yet modelled, and these insights are only up until the design phases. Therefore, the building suppliers of the project have not been included in this analysis.

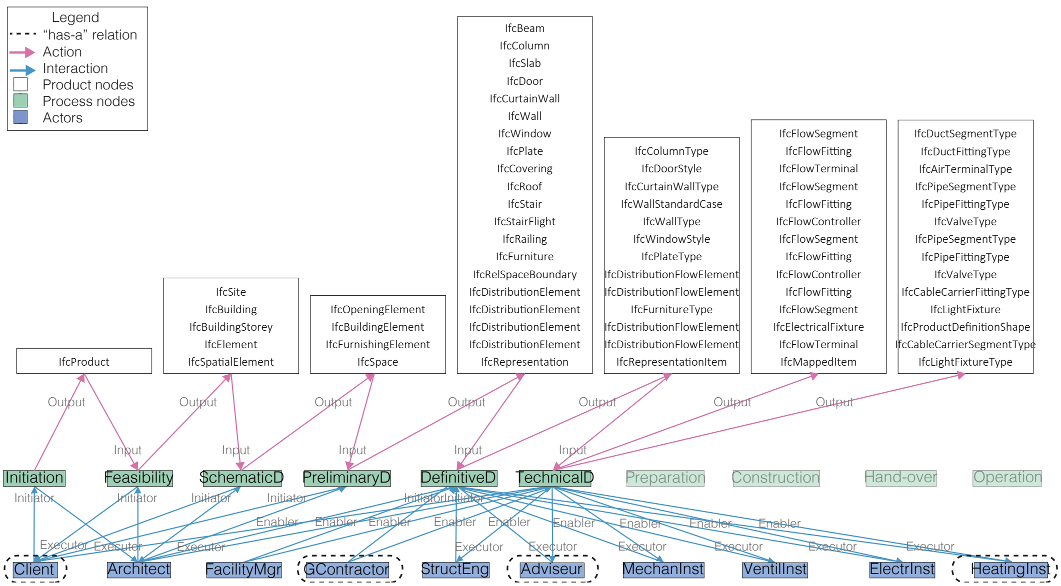

FIGURE 19 Overall view of the model for the ongoing case (The dashed line indicates the internal SC partners.

Apart from offering a structured model for representing the processual, product-related, and organisational complexities of a BIM-enabled SC, this model offers a set of dynamic insights into the SC. Figure 20 contains six analyses of the modelled case. Since the project is still ongoing, estimations for the remaining phases, from preparation to operation, are included as dashed lines in the diagrams of Figure 20, based on the existing case information, provided from the case participants. The following diagrams in Figure 20 illustrate the project complexity regarding product-related (a, b), processual (c, d) and organisational (e, f) complexity.

- The model has 92 modelling entities: 10 actors, 10 phases and 72 product entities (Figure 20, diagram a). The product-related complexity emerges from the Preliminary Design phase when all actors upload their IFC entities on the BIM federated model (Figure 20, diagram b).
- While the first phases last quite long-lasting, the Definitive Design up to Construction had pressing deadlines (Figure 20, diagram c). The latter becomes more intense since the interactions among the SC actors also increase greatly then (Figure 20, diagram d).

- Regarding the organisational complexity, the various SC actors are active in different degrees and thus their interaction is complex and fragmented (Figure 20, diagram e), regardless their organisational position in the SC partnerships, i.e. whether they are internal or external SC partners. The roles of each SC actor are grouped as active (initiator and executor) or passive (enabler) (Figure 20, diagram f).

These quantitative diagrams offer an overview of the project phases and the coordination of the organisational structure of the BIM-enabled SC partnership. These analyses could reveal some deficiencies or gaps in the BIM-enabled project coordination and subsequently underline the areas for further integration the project SC and BIM.

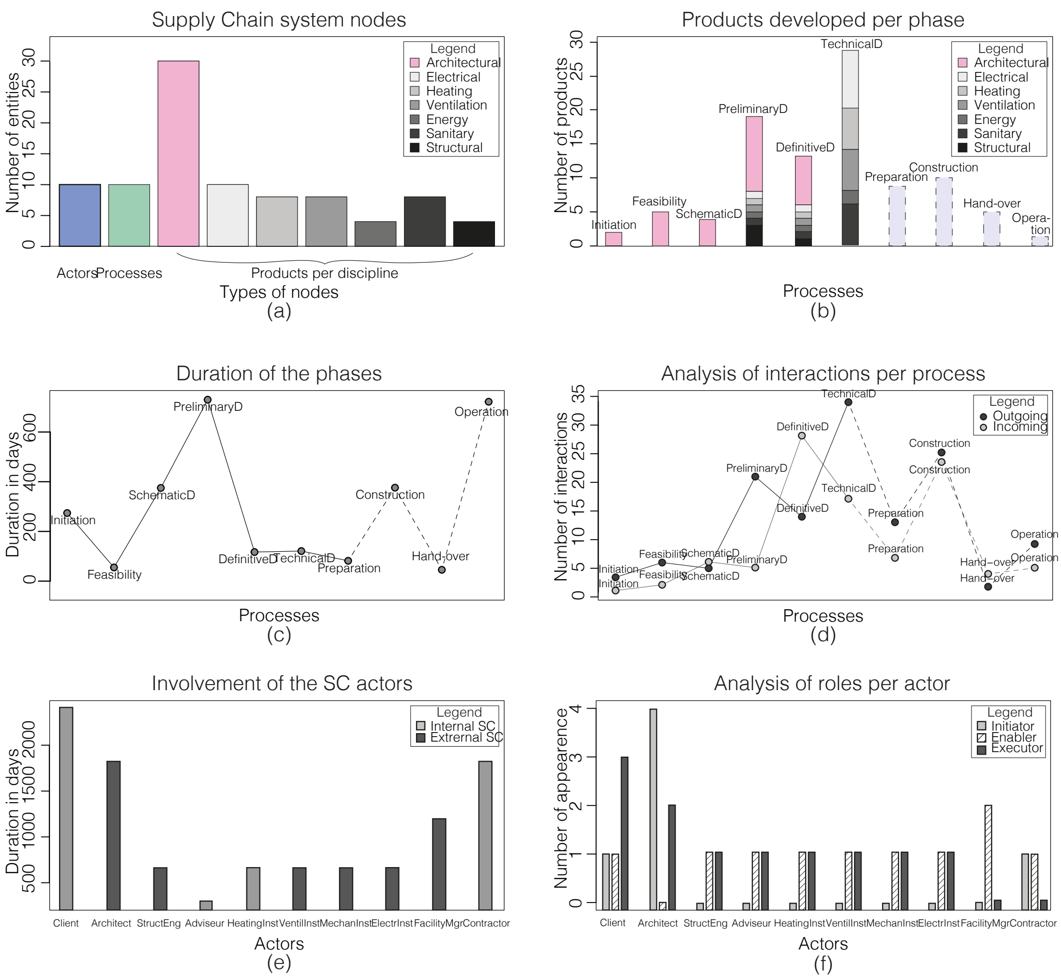

FIGURE 20 Diagrams extracted from the model for analysis of the product (a, b), process (c, d) and organisational (e, f) complexity respectively.

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§ 4.6 Discussion

§ 4.6.1 Impact of the analysis tool

The proposed model analysed a BIM-enabled SC partnership, focusing on the interactions among its product-related, processual, and organisational aspects, with the ultimate goal to investigate the emerging coordination mechanisms in BIM-based projects. The model combined some properties of BIM with SCM concepts and integrated the project information about the products, processes, and actors. Whereas the particular case results are not to be generalised, the further use of the model for the analysis of more BIM-enabled SC partnerships is encouraged. The model conformed to the previously set requirements (see section § 4.4) and performed the following actions for the scenario case:

- Scalability of the model according to various research problems, i.e. projects;
- Integration of the product data from BIM (IFC) to structure the SC information flows;
- Quantifiable analyses of the SC project in tables and diagrams.

In general, modelling is used to analyse a – usually complex – phenomenon and gain insights into its operation that would be otherwise difficult to be obtained from qualitative of analytic methods. The proposed developed model for the analysis of BIM-enabled SC partnerships is by no means complete, but it is a starting point for further development and sophistication of a method to analyse BIM-enabled SC partnerships. Through the case that was used as a proof-of-concept, it could be deduced that the model was useful for modelling and analysing the supply chain. This model has presented a couple of concrete benefits, as well as certain directions for its further amelioration:

- Given that it was modelled is a 'network-type' and not a hierarchical model – which would have been much easier to model in the form of a tree-like, or 'breakdown structure'–, the model is more complex, but also potentially more inclusive and relatable to the real complexities of the phenomenon of BIM-enabled SC partnerships.
- The model could be considered a 'kernel' of principles that could be easily extendable when populated with additional types of entities and relations among them.
- As the modelling decisions used in the proposed model, follow the E-R modelling principles, the complex reality can be easily simplified.
- Given that the concept of coordination is much more difficult to be studied in a networked, rather than hierarchical fashion (which is per se orderly), only a couple of parameters were modelled, for modelling simplicity.
- At the same time, as the model is of an E-R type model, it is largely extendable, and it allows the addition of new parameters (from the spectrum of relations presented in the

background section § 4.2), to shed new light on additional parameters of complexity, with the aim to potentially untangle them. This modelling method is generic and could be further improved.

– Given that the model used tools and open source software, is customisable and flexible.
– As a proof-of-concept, the model presented a palette of analysis' output, and it could be further useful when applied to additional cases.

This modelling approach proposed an analysis tool for projects with BIM-enabled SC partnering. It created a structural relation between the information from BIM applications and interactions among the SC actors. The existing BIM-based collaboration tools only emphasise on access to information, but do not support an analysis of the actors' interactions. These unclear and unregulated interactions among the actors result to poor coordination and information management, and into unregulated information. After all, the construction industry could be largely benefitted by investigating the networks of processes and 'people' in more detail (Aalst et al., 2003). SCM philosophy offers a basis to enrich BIM adoption in practice by emphasising on transparent information flows. The model combined BIM technology with SCM philosophy and aimed at the integration of actor, process, and product information to increase the understanding of the coordination process. The analysis offered insights into the coordination structure and the functioning of the BIM-enabled SC partnering. This analysis tool will be further extended and applied to various configurations in projects of BIM-enabled SC partnerships for calibration, improvement, and validation. Overall, it could be concluded that the model showed a promising way forward to analysing BIM-enabled SC partnerships, as it presented the organisational complexity among actors, the information exchanges among them, and as it is also time-indexed, it could allow for dynamic analyses of the various complexities.

§ 4.6.2 Further considerations

Apart from the afore-described benefits, the proposed modelling analysis tool could be largely improved by accommodating even more structured information. For example, first, by analysing the actors' interactions on a CDE website, the product, processual, actor- related information could be more accurately time-indexed, than simply using the project timelines. The model connects product data stemming from the IFC of the BIM applications – via the process nodes – to the SC actors. The IFC schema encompasses several hundred entities. In an average project, approximately hundreds of thousands of a couple of hundred different IFC entities are modelled. However, not all IFC entities are needed for the proposed model. For instance, "an IfcWindow is not directly related to an IfcWall entity. Instead three other entities are necessary to connect them" (Mazairac & Beetz, 2013). To avoid redundancy in the model, the NIST IFC File Analyzer was used to filter and then discard any geometrical, material and layer properties. In the future, probably a more sophisticated tool or a specialised filtering algorithm could be implemented.

§ 4.6.3 Coordination mechanisms

As the proposed model has been applied to only one real-world case, it is difficult to generalise from the case results. Undoubtedly, other cases might display different coordination mechanisms, depending on their organisational structure. As presented during the introductory section (see section § 4.1) the coordination of BIM projects is a challenging process (Dossick & Neff, 2010; Merschbrock, 2012; Mignone et al., 2016). Therefore, the study of the coordination of BIM-enabled SC partnerships might provide useful insights into how to improve it. Given that lack of trust usually characterises the BIM-enabled collaboration, as Miettiene and Paavola (2014) and Cao et al. (Cao et al., 2015) claim, the mutual trust could be enhanced after the application of SCM principles (Lambert et al., 1996; Mentzer et al., 2001). Therefore, potentially trust and more efficient collaboration could be increased after better coordination of the actors, under a scheme.

In the studied case, the SC partners interacted in a complex manner (see again Figure 19). However, the architect and client played equally central roles to the project (Figure 20, diagrams e and f) even though the architects were external to the SC partnerships. This fact outlines implications for future compositions of BIM-enabled SC partnerships, as probably architects could be deemed important actors for the formation of future BIM-enabled SC partnerships. Although Ling et al. (2014) underline that the client and contractor are drivers of SC integration, the design team is similarly the driver of design innovation for a project (Elmualim & Gilder, 2014). This is corroborated from diagram b in Figure 20, where it is obvious that the architect is the driver of the generation of building information. Likewise, the mismatch between outgoing and incoming interactions suggests the need in certain phases for increased input on behalf of multiple actors, e.g. Design phase. Sebastian (2011b) also underlined this need for input by all involved actors for supporting more long-term considerations in the AEC industry. Considering the project phase when the case was modelled with the proposed analysis tool, a limitation could be that the model only focused on the Design phases, and therefore the input from the suppliers was not taken into consideration. Plus, the analyses derived from the model confirms Shi (2004) that the actors' interactions increase greatly even though the time pressure increases (Figure 20, diagrams c and d). At the same time, the phases between the Preliminary Design and the Construction phases were quite short (Figure 20, diagram c), and this might mean that they could have been potentially integrated.

As previously mentioned in the background section of this Chapter (see § 4.2), there could be numerous inter-organisational parameters able to influence the coordination of a SC, such as power play, hierarchy, trust, and knowledge. As the proposed modelling analysis tool, only included a few of these parameters, a comprehensive image of the coordination in the BIM-enabled SC partnership is improbable. However, the outcomes of the model, displayed an affinity to some structural attributes of coordination, such as the team complexity, distribution of authority, degree of formalisation, and some processual attributes, such as the decision-making process, information and workflow. These attributes could predicate a spectrum of coordination mechanisms, from rigid hierarchies to 'organic' and decentralised developments. According to Olson et al. (1995), the decentralised mechanism of coordination entails complex organisational structures with distributed control, and highly autonomous actors due to a lower level of formal rules (Olson et al., 1995) (see Figure 14). In the scenario cases those attributes were manifested by the division of control across various engineers, regardless of whether they were internal, i.e. strategic, or external SC partners (see Figure 20, diagram e). This decentralised control took place despite the occasional co-locations among the SC actors. Likewise, under the same taxonomy, the decision-making was deemed participative; the information flows largely horizontal due to the properties of the BIM-based information flows, and the workflow was largely concurrent (see Figure 20, diagram d). Therefore, to manage these dependences, all actors' relations and product-related and processual resources should be analysed. From the above, it could be concluded that the coordination mechanisms in the studied BIM-enabled SC partnership were decentralised, rather than centralised, based on Olson's et al. (1995) taxonomy.

Given that the SC partnerships, as defined in this thesis (see Figure 5), are more likely to resemble a network, rather than a hierarchy, it was deemed necessary also to follow a network approach to developing the proposed model (see section § 4.3). However, this does not mean, that the proposed model, can only capture network structures. On the contrary, given that the network approach is inherently flexible and extendable, it could demonstrate a variety of coordination structures, including hierarchies, which are also – basically – networks. Potentially in prestigious projects, where the clients or the architects are more dominant than other actors, the coordination might be more centralised, and thus hierarchical, as these actors might attempt to take control, as a result of the power play among their incongruent interests. Therefore, in prestigious projects, the inter-organisational relations might pertain to hierarchical, rather than network structures. Another example that could be given in the context of centralised coordination structure is when the BIM services are out-sourced to one single company (Aibinu & Papadonikolaki, 2016), that would exert complete control over the coordination of the design and engineering processes.

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§ 4.7 Conclusion

Currently, whereas SCM philosophy and the implementation of SC partnerships in AEC has become popular for its time and cost efficiency, the SC partnerships still appear quite fragmented, mainly due to inefficient collaboration among the involved actors and problematic project coordination. BIM is an aspiring integrator of information flows for the AEC industry, by ensuring structured information sharing through IFCs. However, the coordination of the BIM-enabled projects does not automatically become well-structured, solely because of BIM implementation. More parameters could contribute to efficient coordination, among others, product-related, processual, and most importantly organisational alignment. The implementation of BIM is applied in an ad-hoc manner, despite its acknowledged benefits and the advancements in computing infrastructure. *To combine the SCM and BIM concepts for the further analysis of the coordination mechanisms in BIM-enabled SC partnerships, a graph-based analysis model which integrates various sources of project data, to identify and analyse the organisational, operational, and product-related complexities is proposed* (answer to RQ#3). The model drew inspiration from an analysis of previous modelling and simulation studies on the AEC SC and concluded that the modelling of the actors and their information flows is largely under-represented. As the goal of modelling is apart from gaining 'operational insights' to propose systemic improvements, by exploring the existing coordination mechanisms, it aims to detect bottlenecks and propose tangible actions.

The proposed analysis model utilised building product information and processual information, to represent the state and time changes respectively, combined with actors' information, to represent the interactions among the SC partners. The observed coordination problems in the case that was used as a proof-of-concept included lack of cross-functional planning, which was directly related to processual mismatches, and a lack of explicit organisational structures, especially concerning the architects' firm. Moreover, the model underlined the important role of several 'external' SC partners, such as the design team. Besides merely illustrating the complexity of AEC, the model produced dynamic analyses of the processual and organisational aspects in a real-world case, and afterwards coordination improvements were proposed, for tackling the imbalance in the available processual capacity and the actors' interactions. In the future, the model could be extended with more parameters, and applied to additional real-world cases for calibration to establish a promising tool for analysing, supporting and improving BIM-enabled SC partnerships, by utilising the principles of BIM technology and SCM philosophy, and viewing BIM as an information integrator and SCM as a trusting collaboration setting respectively.

5 Formal and informal inter-organisational relations[7]

Chapter summary

Having performed the empirical (Chapter 3) and conceptual (Chapter 4) underpinning of the relevance for the combination of SCM and BIM concepts, a simplified version of the developed analytical model from Chapter 4, was applied to two cases, for deeper case analysis. Because of the observed derived 'decentralised' coordination mechanisms in the BIM-enabled SC partnerships, the exploration of the various relevant formal, e.g. contractual, informal, and emerging relations was necessary. The previously devised model for the analysis of BIM-based SC partnerships was applied to a set of polar (extreme) cases, recruited by the cases that participated in the empirical exploration study, and namely Cases A and B, which were the cases that displayed the most sophisticated BIM collaboration pattern, i.e. the 'distributed' pattern. The two cases are selected for their advanced BIM-based collaboration, as well as their antithetical SC composition and strategies – one being supply-led and the other demand-led. Although the model was developed with an equal focus on organisations, products, and processes (P/P/A), this deeper case analysis study focused more on the organisational and less on the processual, and product-related aspects.

This chapter focuses on the contractual and digital interdependences between BIM technology and SCM practices in real-world settings (RQ#2). Following a mixed methods approach, the modelling method of Chapter 4 is complemented with case research for the analysis of the contractual (formal), digital (BIM-based), and informal relations, caused by the combination of BIM and SCM concepts. The two methods were combined to increase the research validity by confronting the results derived from quantitative data and findings derived from qualitative data and vice versa. The goal was to discuss the effects of BIM and SCM from multiple actors' perspectives and various data sources. Finally, the modelling decisions that underlined the previously developed analysis tool from Chapter 4 are used to rationalise the complexity and the potential influence of these formal, and informal BIM-enabled SC relations about the performance of the SC partnership. From the analysis, it was deduced that the two construction networks were asymmetric and appropriate strategies were suggested to bridge this gap.

7 This chapter is largely based on a paper under second revision, after invitation to submit to a Special issue on "Social Networks in construction" (Papadonikolaki et al., In 2nd Revision).

§ 5.1 Introduction

The construction industry has employed integrated practices and technologies as a means to control its various intrinsic complexities. Integration is considered as an innovation per se and as a means to stimulate other innovations (Wamelink & Heintz, 2015). Integration pertains to either management approaches or technological means. For example, SC partnerships imply strategic, long-term contractual relations and deploy a SCM philosophy to integrate the flows of material and subsequently information across various firms (Gosling et al., 2015). Likewise, innovative technologies, such as BIM could foster integration of information flows among the multi-disciplinary teams, by improving their collaboration (Eastman et al., 2008) and enhancing project control (Bryde et al., 2013). These two innovations and particularly the involvement of the suppliers in design have been conceptually linked (Nederveen et al., 2010; Nummelin et al., 2011). However, there exists little evidence of their real-world combination, as well as understanding of the inter-organisational impact of BIM-enabled SC partnering.

The representation of organisations as Social Networks (SN) has become increasingly popular in construction research, following on applications in other fields, such as social sciences and economics. The construction industry has been previously considered a system or network of firms by numerous researchers (Dubois & Gadde, 2002a; Bygballe & Jahre, 2009; Larsen, 2011). Pryke (2004, 2005, 2009, 2012) analysed SC partnerships in a quantitative manner using Social Network Analysis (SNA). However, the impact of BIM on such inter-firm relations remains unknown. In this study, SNA is used as an 'analytical language' (Pryke, 2012, p. 13) to explore the inter-organisational impact of combining integrated practices and technologies, i.e. SCM and BIM, considering the various firms within the SC partnership as units of analysis. The term 'SC partnership' instead of 'partnership' is used to describe a set of dyadic partnerships extended across multiple tiers.

Two projects in The Netherlands were used as in-depth cross-sectional studies of the BIM-enabled SC partnerships. The study compared the formal and informal relations among the SC actors. The formal aspects relate to contracts, hierarchies or agreements for online collaboration, whereas the informal aspects relate to the actors' interactions that often circumvent these formal procedures (de Bruijn & ten Heuvelhof, 2008, p. 9; Klijn, 2008). According to Egan's Report (1998), day-to-day communication and information exchange, and knowledge sharing are informal relations. The study in this chapter aimed at exploring, analysing, and understanding the formal and informal relations among the actors that engage in BIM-enabled SC partnerships and the potential influence of the choice for more formal or informal relations on the performance of the SC partnership.

The chapter is structured as follows. The ensuing research background section highlights the research gap, presents the conceptual model, and introduces the research questions (section § 5.2). Next, the methodological justification and the underlying philosophical paradigm to answer these questions follow (section § 5.3). Subsequently, the research results are presented that underline the various formal and informal relations in integrated BIM-enabled SC partnerships (section § 5.4). The results are discussed by confrontation to the relevant literature (section § 5.5). The study concludes with suggestions for bridging the gap between asymmetrical and formal relations versus asymmetrical and informal relations, and recommendations for achieving integration (section § 5.6).

§ 5.2 Background, related research, and research gap

§ 5.2.1 Innovations aiming at integration in construction

Integration has been considered an antidote to the fragmentation of construction projects. Integration refers to the integration of the actors or the integration across project phases (Howard et al., 1989). Regarding actors, integration refers to a project-based team (Baiden, Price, & Dainty, 2006) or inter-organisational teams, beyond organisational boundaries. The latter relates to partnering as an approach to integrating project partners at the supply-side, e.g., contractor and suppliers, or demand-side, e.g., contractor and client, of the chain. Integration has been seen as the higher goal of SCM (Vrijhoef, 2011). SCM is a philosophy that aims amongst others at minimising the interfaces between the various partners, and their operations (Vrijhoef & Koskela, 2000). In the literature from the United Kingdom (UK), SCM has been mainly viewed as a hindrance to competitiveness and free market (Fernie & Tennant, 2013). Pryke (2012) considered SCM, partnering and work clusters as 'governance modifiers' attached to traditional contracts, following on Egan's Report (1998) who envisaged a less contractually formal and more collaborative industry. Whereas SCM has been traditionally linked to performance tracking and an input-output methodology, i.e. a transactional view, informal inter-organisational relations among the project partners are also present in SCM (London & Kenley, 2001), i.e. a relational view. For Leuschner et al. (2013) SC integration related to either an 'operational' or a 'relational' integration among various actors. Apart from focusing on inter-organisational relationships, integration has also been linked to the information flows of design and construction.

Alternatively, integration refers to the various phases of construction. Dulaimi et al. (2002) recognised the integration in the procurement processes, e.g., Design-Build (DB) delivery, and the integration between design and production as equally important to advancing the industry. Apart from merely contractual means to integration, Howard et al. (1989) have proposed computer-aided means to instigate integration across phases, by integrating the information flows among the various disciplines. Dulaimi et al. (2002) emphasised the need that the various actors – from designers to suppliers – adopt compatible Information Systems (IS) to exchange information, and integrate the design and construction processes. BIM can be seen as such a potential solution, given that it allows for the various actors to work on their systems of preference, and simultaneously exchange compatible information, via the Industry Foundation Classes (IFC), currently the main open data standard (Amor, 2015). In this study, BIM could be defined as a set of technologies for generating, sharing, and managing consistent information among the actors, based on the principles of Information Systems' interoperability.

The diffusion of BIM has not been widely considered from an inter-organisational or SC perspective, but rather from the perspective of isolated actors. Table 16 presents scientific literature on BIM adoption and implementation from various actors. Most BIM-related studies have been focusing exclusively and separately on designers, owners or contractors, neglecting the perspectives of sub-contractors and suppliers. Surprisingly, there is a lot of emphasis on the benefits of BIM for Facility Management (FM), despite the paradox that there are significant technical challenges for BIM/FM application (Korpela, Miettinen, Salmikivi, & Ihalainen, 2015). Most of the research on BIM adoption neglects the impact that one party's decision to adopt technology (BIM) has on the remaining actors (Higgin & Jessop, 1965), and subsequently on the formation of a BIM implementation process.

TABLE 16 Scientific literature on BIM adoption and implementation across various project actors.

FOCUS	GOAL	SCIENTIFIC LITERATURE	RESEARCH METHOD
Architect	BIM adoption drivers	(Son, Lee, & Kim, 2015b)	Survey using the Technology Acceptance Model (TAM)
	Factors affecting BIM adoption	(Ding, Zuo, Wu, & Wang, 2015)	Survey using structural equation model
Facility owner	Framework to realise benefits from BIM investment	(Love et al., 2014)	Conceptual model based on resource-based view
	Assessment of BIM competency	(Giel & Issa, 2016)	Delphi method from various maturity matrices
	BIM benefits and challenges	(Korpela et al., 2015)	Survey using cultural historical activity theory
Contractor	Transformation strategies for BIM adoption	(Ahn, Kwak, & Suk, 2015)	Literature review and interviews

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TOC

TABLE 16 Scientific literature on BIM adoption and implementation across various project actors.

FOCUS	GOAL	SCIENTIFIC LITERATURE	RESEARCH METHOD
Supplier	BIM acceptance model	(Mahamadu et al., 2014)	Unified Theory of Acceptance and Use of Technology (UTAUT) and Technology-Organisational-Environmental (TOE)
Installations Engineers	Collaboration with BIM	(Dossick & Neff, 2010)	Ethnographic observations and interviews
Designers & Engineers	Governance of BIM implementation	(Rezgui, Beach, & Rana, 2013)	Interviews with industry participants and focus group meetings
	Responsibility for adopting BIM innovation	(Elmualim & Gilder, 2014)	Literature review and questionnaire survey
Engineers & Contractors	BIM adoption decisions	(Gu & London, 2010)	Interviews with focus groups
Multi-actors (including suppliers)	Adoption and benefits from BIM	(Eadie et al., 2013)	Online questionnaire

As a supply-demand network, the construction industry has a 'cause-effect' relation among the actors. The above in-depth studies have explored BIM technology by isolating actors but ignored their relations to their complementary disciplines across all ties, such as the suppliers. These single-actor studies usually neglect the BIM implementation within inter-organisational environments, and particularly contractually defined SC partnerships. From a multi-actor network perspective, Klijn (2008) suggested that an analysis of the actors' network is crucial to assess the influence of institutional structures further, in this case of BIM adoption, upon the inter-organisational network. Thus, analysing the network of BIM-using actors could offer fresh insights into the emerging relations during BIM implementation.

§ 5.2.2 Social Network Analysis in construction

Following the example of Pryke (2012), this study deploys SNA to represent and understand the relations emerging from SCM and SC partnerships that deploy BIM to integrate their information flows. The roots of SNA are found in sociometry, according to Granovetter (1973, p. 1360). Sociometry was a quantitative method to analyse the social interactions of a set of people via sociograms, i.e. graphs visualising their social interactions and inter-relationships, created by social psychologist Moreno (1960). Wasserman and Faust (1994) defined Social Network as "social structure" of actors (nodes) connected by one or more relations (ties), such as friendship or alliance. The ties are either non-directional, and thus symmetric, or directional, and thus non-symmetric; symmetry reveals whether a relation is mutual from both nodes

(Wasserman & Faust, 1994, pp. 149-150). Apart from structural metrics to describe networks, there are also mathematically founded metrics for SNA, e.g. the concept of centrality for understanding the communication patterns in small groups by Bavelas (1950, p. 727). Graph Theory has provided SNA first with a vocabulary to "label and denote many social structure properties", and second with the mathematical operations to prove theorems about the social structures (Wasserman & Faust, 1994, p. 93). For Scott (2012, p. 63) Graph Theory is a mathematical language for SNA. Among the key concepts of Graph Theory adopted for SNA are the network density and degree centrality. Freeman (1978) identified the relation of the SN centralities to their social implications. The betweenness, degree, and closeness centrality of the nodes represent control, activity, and independence respectively (Freeman, 1978). These metrics have been prevalent among construction management researchers that deploy SNA.

SNA is a popular approach in construction management research. It has often been applied with a project-based focus, as the construction projects consist of essentially "unstable networks that get re-initiated for each project" (Chinowsky, Diekmann, & Galotti, 2008, p. 806; 2010, p. 453). The unit of analysis could be either isolated social actors, i.e. a social network, or firms, i.e. an organisational network. SNA was used by Thorpe and Mead (2001) to analyse the communication among project teams from different firms and compare it to their use of Project-Specific Web-Sites (PSWS). Among their most interesting findings, was that the project teams circumvented the traditional communication channels and hierarchy to speed up the communication (Thorpe & Mead, 2001). Chinowsky *et al*. (2010) used SNA to study the information exchange in construction firms and reveal the relation between actors' and firm's performance. Other SNA studies focused on the informal aspects, such as knowledge, trust, and awareness (Morton, Dainty, Burns, Brookes, & Backhouse, 2006, respectively; P. Chinowsky et al., 2008; Larsen, 2011). Pryke (2002, 2004, 2005, 2012) applied SNA to analyse the inter-organisational transactions as to information exchange, performance incentives, and contractual relationships and revealed the relationship between innovative procurement, new roles, and communication patterns. These last studies have demonstrated the applicability of SNA in inter-organisational settings to analyse formal and informal relations simultaneously. Table 17 summarises and categorises some influential studies in SNA in construction, from well-established journals on construction and project management, as to their focus, nodes, and ties analysed, to show the variety of research goals and methods for SNA in construction.

TABLE 17 Taxonomy of studies applying SNA regarding the focus and the modelled entity.

FOCUS	NODE	TIE (LINK)	SCIENTIFIC LITERATURE	SNA METRIC USED
Intra-organisational	Employees	Awareness (informal)	(Larsen, 2011)	Network density
	Employees	Physical communication (formal and informal), also inter-organisational focus	(El-Sheikh & Pryke, 2010)	Degree centrality, closeness centrality
	Employees	Physical communication (informal), also project-based focus	(Loosemore, 1998)	Degree, betweenness, and closeness centrality
Project-based	Employees	Physical communication (informal)	(Chinowsky et al., 2008)	Betweenness centrality
	Employees	Physical communication (informal)	(Alsamadani, Hallowell, & Javernick-Will, 2013)	Network density, degree and betweenness centrality
	Employees	Digital communication (formal)	(Hossain & Wu, 2009) and (Hossain, 2009)	Network density, degree, betweenness, and closeness centrality
	Firms	Hierarchical leadership (formal)	(Solis, Sinfield, & Abraham, 2012)	Network density, centrality, and structural equivalence
	Firms	Physical communication (informal)	(Wambeke, Liu, & Hsiang, 2011)	Degree and eigenvector centrality
	Firms	Physical (informal), digital communication (formal)	(Thorpe & Mead, 2001)	Degree centrality
	Firms	Knowledge (informal)	(Chinowsky et al., 2010)	Network density
	Firms	Knowledge (informal)	(Ruan, Ochieng, Price, & Egbu, 2012)	Network density, degree, betweenness, and closeness centrality
Inter-organisational	Employees	Physical communication (informal)	(Pryke, Zagkli, & Kougia, 2011)	Network density, actor (degree) centrality, and tie strength
	Employees	Financial incentive (formal)	(Pryke & Pearson, 2006)	Degree centrality
	Firms	Physical communication (informal)	(Pryke, 2004, 2005)	Degree centrality
	Firms	Performance incentives and contracts (formal)	(Pryke, 2005)	Network density, degree centrality
	Firms	Contracts (formal)	(Park, Han, Rojas, Son, & Jung, 2011)	Network density, degree centrality
	Firms	Contracts (formal)	(Chowdhury, Chen, & Tiong, 2011)	Degree, betweenness, closeness and eigenvector centrality
	Firms	Contracts (formal)	(Sedita & Apa, 2015)	Network density, average path length, betweenness, and closeness centrality
	Firms	Contracts (formal)	(L. Liu, Han, & Xu, 2015)	Degree distribution, average path length, and clustering coefficient

Surprisingly, in Table 17, most studies contain data on physical communication collected retrospectively via interviews, questionnaires, and surveys from participants. Such data collection methods could further allow for “impression management and retrospective sense-making” (Eisenhardt & Graebner, 2007). There are only a few studies (Hossain, 2009; Hossain & Wu, 2009) on measuring the interactions among the actors using tangible data sources, such as their interactions over digital means. Guo et al. (2013) have also underlined the need to investigate the actor’s interactions on digitally enabled infrastructures, rather than by analysing data collected via surveys. Charalambous et al. (2013), in an effort to demonstrate the redundancy of email-based communication in BIM-based projects, used SNA to represent the distribution of actions among the project actors using an online platform. Data collection for SNA from online platforms minimise the informants’ biases.

In Table 17, both formal and informal ties have been studied with SNA. However, the formal aspects, such as the contractual relations, or the financial and performance incentives, which are inherently tangible, are most suitable for analytical research methods such as SNA. Exceptions are also possible, as Buskens (2002) used SNA to evaluate trust and explore the structure of simplified networks where all actors were equally important. In Egan’s Report (1998) the contracts and other project documentation are ‘formal’ relations pertaining to management and organisation, whereas the day-to-day communications pertain to the ‘informal’ aspects of management and organisation. However, some contractual relations could be also classified as informal, such as long-term relations (Pryke, 2012, p. 177). Similarly, whereas the information exchanges are classified as ‘informal’ relations as they are implicitly and not explicitly contractually defined (Pryke, 2012, p. 146), according to Pryke (2012, p. 17) the information exchanges are not necessarily only informal. In the context of BIM, where BIM-learning and trust are informal aspects, the interactions over digital means, such as PSWS, also known as Common Data Environment (CDE), are formal collaborative relations, as these are explicitly prescribed in BIM Execution Plans.

§ 5.2.3 Research gap and Conceptual model

As shown in Table 16, there is a lack of studies addressing BIM from an inter-organisational – or SC Management – perspective focusing on a construction network across multiple tiers, from designers to suppliers. Simultaneously, SNA is a fruitful analytical method to analyse the supply chain relations (Table 17) as multi-actor networks and not as hierarchical contracts, which are relatively more rigid, uniform and unilateral (de Bruijn & ten Heuvelhof, 2008, p. 10). SNA studies could shed light on the various formal and informal relations of BIM-enabled SC partnerships. Before presenting the research questions about the relations in BIM-enabled SC partnerships, previous studies on BIM and SC integration were reviewed.

BIM has been linked to the SCM philosophy from various researchers and both positivist and interpretivist standpoints. Nederveen *et al*. (2010) envisaged the need to include all the members of the SC in the decision-making, e.g., the suppliers and the client, so as to play a more dominant role in the design process. Mahamadu *et al*. (2014) reported that BIM has become a prerequisite for the selection of suppliers for project delivery. Nummelin *et al*. (2011) performed expert workshops and identified possibilities for BIM and SCM combination, e.g. design management, site management, and cost management. Whereas BIM and SCM have been deemed compatible approaches, there is little and contradicting evidence on the impact of their combination. For example, whereas Navendren *et al*. (2014) observed a lack of supply chain integration, given that some manufacturers in the UK were not convinced of the value of investing in BIM, Dike and Kapogiannis (2014) reported on the "collapse of the traditional adversarial culture inherent in the UK construction" and indicated that early BIM adoption could facilitate trust among the firms.

In the UK, the 'intelligent' information flow, derived from BIM models and based on principles of IS interoperability, has been previously considered as an enabler for supply chain integration (CIC, 2011). Undoubtedly, as BIM has not yet reached a high level of maturity at an industry level (Kassem et al., 2015), its implementation entails a set of interdependent activities similar to the concept of 'clusters' of a multi-disciplinary team that operates in a non-hierarchical manner, e.g., 'technology clusters' (Gray, 1996). The governance of such technology or work clusters is problematic for the industry, as those are incompatible with the "standard dyadic forms of contract in use alongside various partnering arrangements" (Pryke, 2012, p. 60). Hence, an analytical approach to representing and understanding such multi-disciplinary clusters, and particularly BIM-enabled SC partnerships, is preeminent for exploring BIM and SCM innovations. To this extent, SNA is the vessel for analysing BIM-enabled SC partnerships and especially the choice between their formal and informal aspects, as well as their impact on the chain's performance.

The various contractual partnering means imply a deeper commitment to cultural transformation or, at least, a prior cultural compatibility among the chain (Bresnen & Marshall, 2000, pp. 233, 234). Therefore, alongside formal agreements and top management's support, informal aspects of collaboration such as communication, trust, culture, knowledge transfer, and attitude to change, also play a role in integrating the multi-actor network. There is a need to investigate the informal dimensions in BIM-enabled SC partnerships, given that although BIM carries the potential to transform the collaboration (Dossick & Neff, 2010), it cannot completely replace other IS such as emails, databases and information exchanges over CDE (Demian & Walters, 2014). BIM implementation also depends on informal processes, which are not necessarily accompanied by formal structures. These informal BIM processes add to the complexity of formal relations and affect the performance of the chain. Figure 21 illustrates the conceptual model of this study.

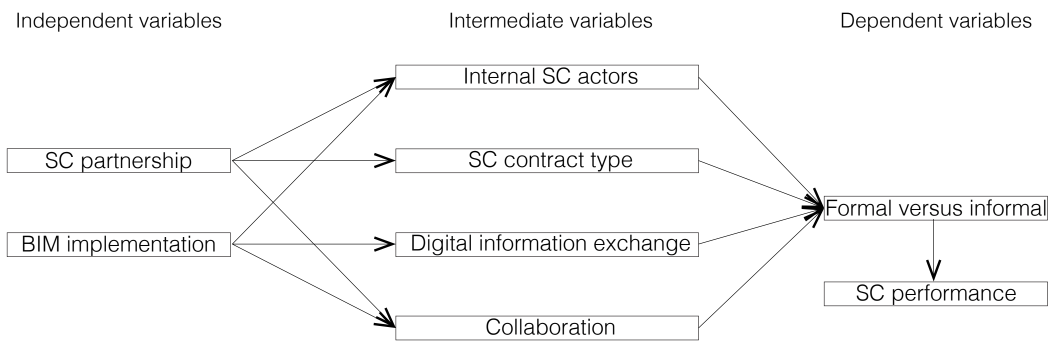

FIGURE 21 The conceptual model of the study and the relation between the research questions.

These informal BIM processes also add to the informal aspects of the inter-organisational relations. This chapter explored the key *RQ#4: What are the effects of BIM-enabled SC partnering on the formal and informal relations of the Supply Chain?*, by dividing it into two sub-questions and sets out to explore the following:

- What formal and informal relations of firms in BIM-enabled SC partnerships can we distinguish?
- How does the choice of formal and informal relations of BIM-enabled SC partnering affect the performance of the SC partnership?

§ 5.3 Methodology

§ 5.3.1 Mixed methods approach

Rationale

Thinking in terms of systems originated from the need to respond to multi-dimensional problems beyond black-box approaches. The focus on operations and Operations Research (OR) emerged during the interwar period. Systems Thinking theories emerged soon after World War II and offered a more constructivist approach to the positivism of OR (Klir, 2001). Klir (2001) defined system as a set of certain things, *thing-hood*, and a set of relations among that set, *system-hood*. 'Network' is a newer term than 'System', and it relates to the representation of a set of things (nodes) and a set of relations (links), i.e. a system. Network Science began with Granovetter's (1973) studies on the ties among social groups. The construction industry has been described as a system or network of firms with an emphasis on their relations (Dubois & Gadde, 2000, 2002a; Bygballe & Jahre, 2009). These networks exist at a project or market level and are temporary or permanent. The main challenge of such networks is the complexity of the many involved firms and their inter-relations (Gidado, 1996; Winch, 1998; 2002). The existing qualitative approaches to managing complexity in construction networks lack the ability to grasp the multi-faceted relations among firms.

Larsen (2011) recognised that for complexity, both a positivist approach, focusing on the structure of the system, and an interpretivist approach, focusing on the actors are needed. In SCM research, there has been a need for a more balanced approach between "inductive research methods (typically qualitative) in addition to deductive methods (typically quantitative)" (Golicic et al., 2005). After all, SNA, despite being considered a merely quantitative tool, has also been used for interpretative analyses (Loosemore, 1998) or analysis of trust (Buskens, 2002). In Table 17, SNA has been primarily used in project-based studies. As this study focused on inter-organisational construction networks and particularly SC partnerships, it used SNA as a methodological tool to represent and understand them.

Mixed methods were applied, to balance the deductive and inductive thinking. The mixed methods consist of case study research through qualitative data, and SNA and modelling using quantitative data. The SN and modelling analyses (deductive) were used to describe, explain, and compare the explicit formal relations to the informal inter-organisational structures. These relations stem from emerging BIM-based collaboration and provide an answer to the formal part of the first research question. The case analyses (inductive) were used to describe and interpret the complexities of two BIM-enabled SC partnerships and provide an answer to the informal part of the first and second research question.

Case study selection

Two cases of BIM-enabled SC partnerships in the Netherlands were analysed, to examine the inter-organisational relations. The cases were cross-sectional studies of interaction episodes of the two chains, embedded in their time and space context (Gadde & Dubois, 2010). The Netherlands was selected as the location for these analyses because of the popularity of BIM and SCM practices. First, SCM and SC partnerships in the Dutch construction industry have been popular for replacing the traditional tendering processes (Vrijhoef, 2011). The innovation of SCM in procurement processes lies in that simple and short documents are used to prescribe the SC partnerships, i.e. framework agreements (Pryke, 2002). These SC partnerships were based on pre-existing long-term relations that aim at increasing process and product quality. Second, the implementation of BIM in the Netherlands has been quite advanced (Kassem et al., 2015). Thus, the existence of quite advanced levels of both SCM and BIM suggests a relevant locale for the study.

The two cases could be considered *polar* cases (Eisenhardt & Graebner, 2007), due to their different contract types and BIM implementation approaches. The intention is through the analysis of these extreme cases to generate insights into a spectrum of BIM-based projects. For Flyvbjerg (2006) extreme cases usually "reveal more information because they activate more actors", rather than simply analysing mechanisms in similarly procured BIM-based projects. The deployed BIM-related and strategic processes of the polar cases could suggest steps for further integrating other BIM-enabled SC partnerships. After all, Bengtsson and Hertting (2014) claimed that the findings from case studies could be generalised when 'expectations about similar patterns [...] in similar contexts' take place, in this case of similar settings of BIM-enabled SC partnering. And although the two cases are polar, they still take place at similar BIM-enabled SC partnering contexts.

Case study A was the construction of a multi-functional building complex, which consisted of three buildings with 255 residential units, offices and commercial spaces, located next to a canal. The contractor, client, heating and energy firms, and the facility manager formed the SC partnership, in the form of a multi-party contract for 20 years, namely UAV-GC (Uniform Administrative Requirements for Integrated Contracts). Besides this UAV-GC contract, there were also bipartite SC contracts. BIM was applied from the Preliminary Design until Pre-construction and would be used for the maintenance, and thus the duration of these phases was the time setting of the case study.

Case study B concerned a housing tower, with 83 housing units over a pre-existing building, resulting in high technical complexity. The contractor had SC contracts with the architect, structural engineer, steel sub-contractor, and suppliers, e.g., windows, cladding, and roof. BIM was applied from the Initiation until Construction, and "as-built" BIM would be delivered. The main difference between the two cases was the type of contractual relations. Another difference between the two projects was their scale, given that the project of case A was much larger. This diverse nature of the two cases could generate insights into a variety of projects. Table 18 summarises the most distinctive key characteristics and differences of the polar cases.

TABLE 18 Description of cases A and B.

CASE A	CASE B
Multi-party UAV-GC contract	Bipartite contractual relations stemming from the contractor
The contractor has a wide project portfolio	The contractor has a dry construction project portfolio
The architect was external to the partnership	The architect was internal to the partnership
The client was internal to the partnership	The client was external to the partnership
The suppliers were contracted at pre-construction	The suppliers were contracted after Definitive Design
UAV-GC contract for 20 years maintenance	No maintenance plans, but as-built BIM delivery
Large multi-functional project	Medium housing project
Special energy requirements	No special energy requirements

§ 5.3.2 Empirical explorations

Case study design and data collection sources

The overarching method was case study research. The cases were selected for providing a "real-life context" to the study (Yin, 1984). The focus was inter-organisational, i.e. the relations among the firms. The case study design did not concentrate on the 'focal' firm of a SC partnership, e.g., the contractor, instead devoted equivalent time to all partners. The number of the interviewees was not proportional to the cases' scale, due to the fewer interviewees in Case A. Despite being a research limitation, the lack of interviewees could also indicate lower SC integration from Case A. Whereas the unit of analysis was the firm – for the exploration of the formal relations via SNA – to ensure a grounded understanding and avoid biases (Eisenhardt & Graebner, 2007) employees from various hierarchical levels were interviewed for the exploration of the informal relations. Within the engineering firms, three functions were interviewed to grasp the informal relations: the project/tender manager, the lead engineer, and the modeller. In smaller firms, these functions were combined in one position. Interviewing various functions within each firm contributed to acquiring additional intra-organisational insights. Table 19 presents these interviewees.

TABLE 19 Interviewed firms and employees for the Phase III of Case A and B.

CASE A			CASE B		
Firm	Role/position	BIM user	Firm	Role/position	BIM user
Facility Manager	Project Manager		Contractor	Project Leader	
Contractor	Site Engineer	x	Contractor	Site Engineer	x
Contractor	BIM Manager	x	Architect	Project Architect	x

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Contractor	Design Coordinator	x	Architect	BIM Modeller	x
Architect	Project Architect		Structural Engineer	Lead Engineer	x
Architect	BIM Modeller	x	Mechanical Engineer	Tender Manager	
Structural Engineer	Director		Mechanical Engineer	Site Engineer	x
Structural Engineer	BIM Modeller	x	Mechanical Engineer	BIM Modeller	x
Mechanical Engineer	Project Leader	x	Sub-contractor B1	Project Leader	
Supplier (Supp2)	Tender Manager		Supplier (Supp3)	Director	
Supplier (Supp2)	BIM Engineer	x	Supplier (Supp3)	BIM Modeller	x

The data collection sources were:

- Case documents (SC contracts and BIM protocols).
- Data from the project's website (CDE) on the digital information exchanges.
- Interviews with the main project actors (Table 19) about the project and the SC.

Case study protocol

The interviews were semi-structured and had consistent preparation and data handling. Before the interviews, all interviewees had the same information about the study goals and the concepts of SCM and BIM via a template document. Question hand-outs were administered at the beginning of the interview (see Appendix C). The questions concerned the firm's about engaging in SCM and using BIM, SCM and BIM implementation within the projects, and a reflection on the projects' performance. The interviewees were free to choose their preferred language for the interview, and all interviewees chose Dutch. The interviews were recorded to aid the transcription and translation. Five research assistants, who were present in the interviews, worked on the transcription and translation of the audio recordings. The transcripts were analysed with qualitative analysis software, using free codes. The firms welcomed the use of their input for research but were sensitive to the publication of their contact information. The authors were not affiliated with these firms.

§ 5.3.3 Modelling explorations

Organisational Network Analysis method

The SNA was used as a "natural complement" to the cases (Eisenhardt & Graebner, 2007). Following Larsen (2011), SNA is considered embedded in the positivist paradigm, given that it embarks from abstraction, rather than interpretation. The

SNA analysed the various multi-disciplinary firms (actors) and their relations (links), i.e. the Organisational Network (ON). The SNA was used to model and analyse the inter-organisational networks based on their contracts, following the approach used for contractual analysis in the work of Pryke (2002, 2005, 2012). The node degree centrality and weighted degree in the two cases were calculated using Gephi software (Bastian et al., 2009). The SNA analysed the contractual relations (from document analysis) and the digital information exchanges (from the IFC exchanges on the CDE) in the BIM-enabled SC partnerships. The information exchanges were measured via the CDE, rather than post-hoc questionnaires, to minimise the 'impression management' (Eisenhardt & Graebner, 2007). The informal relations of collaboration were analysed qualitatively through the afore-mentioned questionnaires, as they could not be captured digitally.

Temporally indexed Organisational Networks emphasising on information flow

A complementary to SNA approach was undertaken to include the non-contractual, but BIM-based interactions. Apart from using the case documents, such as contracts and BIM protocols, the digital interactions of the actors on the project-specific website (PSWS) or CDE – as specified in the guidance given under Publicly Available Specifications (PAS) 1192, to coordinate information among project actors – were analysed. This data source incorporates the timing parameter, which is important for understanding the evolving nature of the multi-actor construction networks.

Through the CDE, apart from the organisational and processual data about the projects, building information was also extracted. The CDE stored the information about the responsible actor, the date and the shared building information type. The building information was obtained from the uploaded IFC files. The IFC files were subsequently analysed with the NIST IFC File Analyzer (Lipman, 2011). The data were harvested in spreadsheets and analysed quantitatively. The data were collected from the Definitive Design (DD), Technical Design (TD), and the Pre-construction (Pre-C) when the engineers' and suppliers' information was merged. The data for the two cases were collected over a period of 11 and 8 months respectively. The DD, TD, and Pre-C phases lasted for the two cases 3, 2, 6, and 3, 1.5, 3.5 months respectively. These phases are equivalent to RIBA Plan of Work (Sinclair, 2013) 'Developed Design' and up until the end of the 'Technical Design' phase.

The CDE provided data on the ON, the processual, and product (IFC) information and was analysed to represent the complexities of BIM-enabled SC partnerships. Through this analysis, the relations among the ON and the digital information exchanges were captured. Figure 22 illustrates the relations among the actors (ON), time indexing parameter, and exchanged digital information (IFC). An additional goal was to offer new insights into network theory and its applicability to project-based SC research.

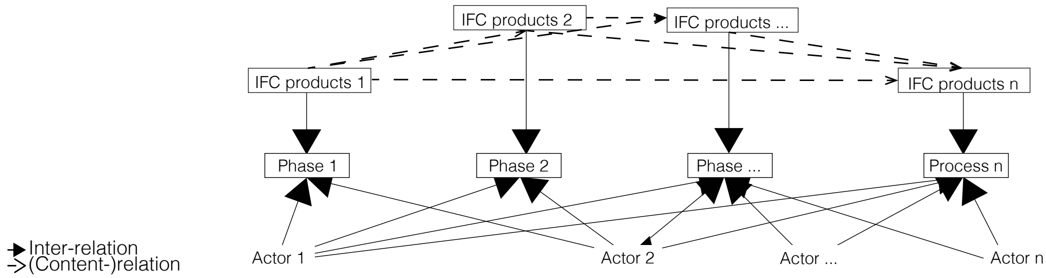

FIGURE 22 Relations between concepts of actors, phases and building information from the CDE.

§ 5.4 Case results: Description, analysis, and interpretation

§ 5.4.1 Contractual relations

Four main types of contractual relationships were observed in the two cases. In increasing order of commitment, these contracts were: (a) normal tendering contract, (b) preferred partners, (c) SC framework agreement, and (d) UAV-GC contract. The UAV-GC – used in Case A – is an integrated form of contract, which has a strong project-based focus and could in some projects reflect prior partnering commitments and further encourage future long-term relations. The UAV-GC is similar but involves more explicit financial agreements than a Design, Build & Maintain (DBM) contract. UAV-GC contracts are usually created among clients, consultants, and contractors to provide information that can be re-used across projects and inspire long-term goals, e.g. maintenance. The actors of Case A had previous collaborations, but the sophisticated UAV-GC contract was a new formal structure for their SC. The SC framework agreements are short two-party documents, that seem simple (Pryke, 2002), and focus on their long-term collaboration for a pre-agreed duration, and further either on price or quality aspects, or both (Macneil, 1977). In Case A, BIM was a contractual requirement for most involved firms. In Case B, the SC agreement also contained a BIM clause for the engineers. In both cases, the contractors also held agreements with some engineers, sub-contractors or suppliers, who formed a pool of 'preferred partners.' These preferred partners were firms supposedly already culturally aligned to the contractors. The final selection of the preferred partners was made by the availability of culturally compatible individual employees. Figure 23 illustrates on the top part the contractual relations, and below the type of exchanged digital information. The tendering contracts are shown as arrows pointing at the tendered party, and the partnerships are shown as simple weighted lines according to the longevity of the relation. Table 20 presents the network analysis of the involved actors in the cases based on their degree centrality and weighted degree centrality.

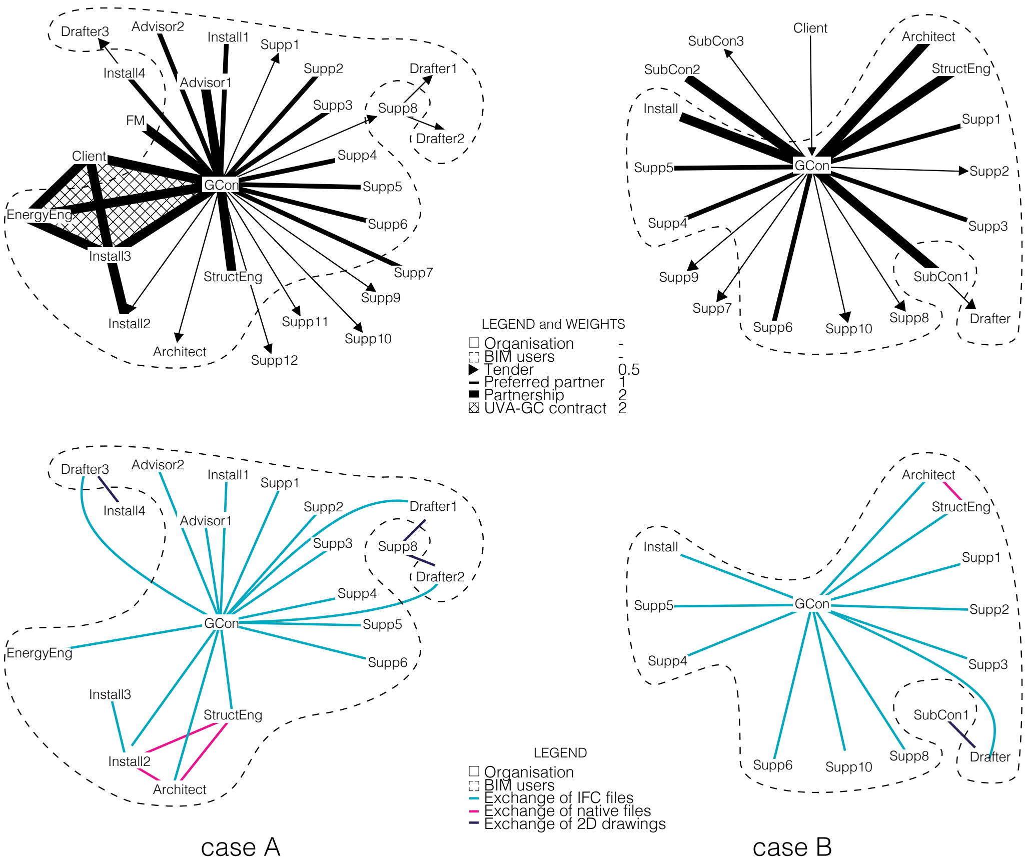

FIGURE 23 Contractual relations, BIM users (top), and type of digital information exchange in cases A and B (lower part).

TABLE 20 Node degree centrality, weighted centrality (see Figure 23), and BIM use for the actors.

CASE A				CASE B			
Firm	Degree centrality	Weighted degree	BIM user	Firm	Degree centrality	Weighted degree	BIM user
GCon(tractor)	23	31.5	x	GCon	17	20.5	x
Install3	4	8	x	SubCon1	2	2.5	
Client	3	6	x	Arch	1	2	x
EnergyEng	3	6	x	StrEng	1	2	x

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TOC

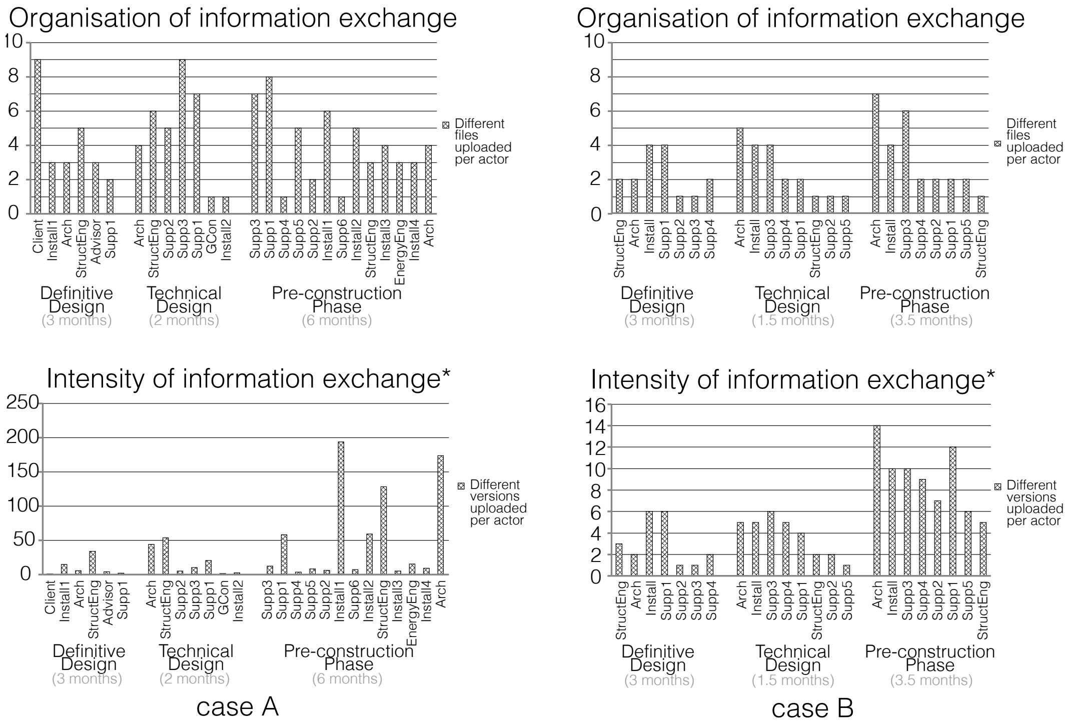
Supp8	3	1.5		InstEng	1	2	x
Install4	2	2	x	Supp1,3	1	1	x
Install2	2	2.5	x	Supp2	1	0.5	x
Advisor1,2	1	2.0	x	Client	1	0.5	
StructEng, Install1, Supp2,3,4,5	1	2.0	x	Drafter	1	0.5	x
Supp1,6	1	1.0	x	Supp4,5,6,8,10	1	1	x
Supp7	1	1.0		Supp7,9	1	1	
Supp9,10,11,12	1	0.5		SubCon2	1	2	
Architect, Drafter1,2,3	1	0.5	x	SubCon3	1	0.5	x
FM	1	2.0					

The two cases had different contractual schemes. In Case A, the SC had a strong project-based focus, given that the contractor, the client and two installation firms formed the UAV-GC contract. The architect was traditionally tendered by the contractor. The rest of the actors were either tendered or had long-term contractual agreements with the contractor. In Case B, the partnership was formed by 'dyadic' relations initiated by the contractor. The architect had an exclusive relation with the contractor. The contractor also had an exclusive relation with the structural engineer, but this was not reciprocal, i.e. the structural engineer worked also with other contractors. From the centralities of Table 20, the contractor of Case A is more active than the contractor of Case B, due to the quantity and quality of contracts they held.

The dashed line in the lower part of Figure 23 encircles the BIM-using actors to indicate the so-called "BIM-chain" consisted of the BIM-using actors who applied it for delivering their services. Note that not all strategic partners of the SC partnerships were BIM users. The agreements upon the BIM protocols were reached differently in the two cases. The BIM protocol of Case A was created by the contractor, who had an in-house BIM manager, responsible for all BIM-based projects and an additional project-based BIM coordinator. The BIM protocol and the BIM implementation strategy of Case B were initiated from the desires of the SC partners, who were long-term partners with the contractor. The two BIM protocols had similar document structure and included the introduction, project scope, scope of BIM and SCM, phasing and work organisation. Although both BIM protocols included the identities of the involved parties, the BIM protocol of Case A included detailed responsibilities of the parties pertinent to communication and division of work. These differences imply a 'top-down' BIM implementation in Case A and a 'bottom-up' BIM implementation in Case B. The lower part of Figure 23 shows the type of information exchanged among the BIM-using actors. In Case A, frequent exchanges of native BIM files took place (Figure 23, magenta lines). In both cases, some firms out-coursed BIM to third parties (dark blue lines).

§ 5.4.2 Analysis of the digital information exchange

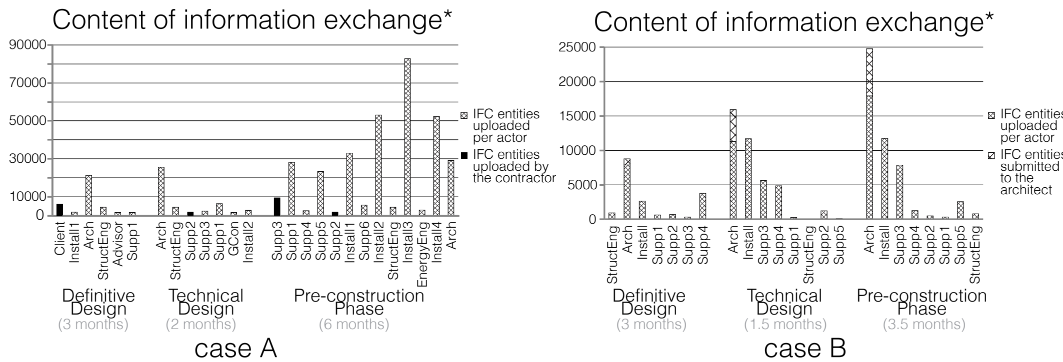
The analysis of the files uploaded on the CDE was performed at two levels regarding the quantity and the content of the exchanged information. The quantity of the files uploaded on the CDE was analysed as to the organisation of the information exchanges and their intensity, as illustrated in Figure 24. The diagrams on the top indicate the number of IFC files uploaded per phase from each actor. The differences of file numbers and versions of the two cases are due to the projects' complexity. The project of Case A was divided into four components (three buildings and one parking garage), which were developed and managed consecutively. In Case B, the project was smaller and the building project information was organised into two main components: the housing volume and its connection to pre-existing structures on site. In both cases, the other engineers and suppliers created as many different files as the number of different building systems they were designing or producing. The interactions were more intense (frequent) in Case A. This difference could be explained not only from the project's organisation but also from the special energy demands (solar and geothermal) that required multiple reviews among the involved actors. Moreover, Case A had four different installation firms (energy, sanitary, electrical, and mechanical engineers), while Case B had no special energy demands and only one integrated firm provided all installation services: Mechanical, Electrical, and Plumbing (MEP).



*Note that the axes of the diagrams from Case A and Case B have different scale.

FIGURE 24 Organisation (files per actor) and intensity (versions per actor) of information exchanges (IFC) in Case A and B.

The second level of analysis of the IFC files from the CDE concerned the content of the exchanged information. The number of the IFC entities per discipline indicates the division of work among the various actors. Figure 25 illustrates the analysis of the content of the information exchange. In Case A, the federated model consisted of thirteen segregate models from the various actors, while in Case B from eight. In Case, A, an additional combination of proprietary files was made using information from the engineers. This analysis revealed two different types of information exchange among the SC actors. In Case A, the contractor uploaded some information on behalf of suppliers. In Case B, the architect was keen to integrate information from some suppliers directly to their architectural model, bypassing the file uploading process on the CDE.



*Note that the axes of the diagrams from Case A and Case B have different scale.

FIGURE 25 Analysis of the content of information from each actor per phase.

§ 5.4.3 Informal aspects of BIM-enabled SC partnerships

The reflections from the cases were analysed as to the informal aspects of communication among the project partners and particular in connection with BIM implementation. In Case A, the communication took place through the exact channels described in their contracts. The architect, the mechanical and the structural engineer always communicated through the contractor, with whom they had contracts, or made sure to carbon copy them. However, the supplier, who had a 'chain contract' (SC framework agreement) with the contractor, sought direct channels to communicate with other suppliers or engineers: *'and we must call other suppliers to solve problems with other suppliers. We should not expect to have all the communication pass through the contractor'* (Supplier-Tender Manager-A). Surprisingly, the communication run solely either among the engineers or the suppliers respectively. The engineers (architect, structural and mechanical) had no relations with the suppliers. The supplier, structural and mechanical engineers often discussed the partnership as an approach to managing the financial uncertainties and build trust. However, the contractor admitted that *'at this project the supply chain cooperation has not happened well because it has been approached from the money perspective'* (Contractor-Design coordinator-A). The architect held a depreciated role in the project because they were hired to develop an existing concept design of a previous architectural firm. The architect agreed that they did not have explicit agreements on the design and the materials with the contractor. The contractor should *'actually have agreed on the details in the earlier stages with the architect'* (Supplier-BIM Engineer-A). Regarding the performance of the SC, the discussions were at a strategic level: *'there is a lot expected of us that normally cannot be expected to be performed; it is a quite one-sided story on behalf of the contractor to us but also towards the other parties'* (Mechanical-Tender Manager-A). In the contractor's firm they reflected and admitted that *'eventually to go well the* *collaboration process was more important than just the money'* (Contractor-Design coordinator-A).

In Case A, BIM was adopted to potentially facilitate the maintenance of the building, as requested by the UAV-GC contract. Concerning BIM implementation, the contractor admitted that although a BIM protocol was defined early in the process, the respective details, such as the LoD, standards used for details of information exchange were *'not unanimously agreed among the parties'* (Contractor-Design coordinator-A). However, the role of the BIM coordinator (firm level) and BIM manager (project level) was well-defined in the project. The contractor firm's BIM knowledge *'has gone up considerably, and they* (the BIM coordinators) *may also spend time on our subcontractors to solve export problems physically, or they come here*' (Contractor-Design coordinator-A). Therefore, the BIM challenges stemmed from the inter-organisational and contractual relations, rather than technical BIM issues. The suppliers were not considered strategic from the contractor and involved quite late in the project. Thus, given that different clash sessions were hosted per building unit and among the disciplines, not all parties were familiar with each other. *'We need to have permanent contact persons in the companies; this is where the SCM and BIM should have been intertwined'* (Supplier-BIM Engineer-A). Whereas some suppliers had advised the contractor earlier during the tendering stage, they were informed to start working on the project at short notice *'and the information was not far yet*' because meanwhile they had not been briefed accordingly (Supplier-BIM Engineer-A). Finally, the project was behind schedule due to changes from a Design-Build to a UAV-GC project, by tendering the new architect and imposing various special energy requirements. Some co-locations took place only after the start of construction to solve problems on site.

In Case B, the communication took place through channels beyond the formal contractual agreements. The SC partnership was formed having the main contractor as a node connecting the various engineers and suppliers (Figure 3). However, the communication usually bypassed the contractor and was directed from various partners towards the architect, via informal channels, e.g. email, telephone: '*So it is not only in meetings, questions are also asked in e-mails. Or by phone; I now need something, then you call each other. We are also very used to come together to sit down and discuss things with each other. In many ways, the information goes back and forth'* (Project Architect-B). The partnering relation of the contractor to the architect made the latter more approachable to other actors: '*So our real role* (towards the partners) *is only good collaboration and making clear agreements about that. I know that sounds crazy to be our only role*' (Project Architect-B). There was a recurring pattern of statements about the higher value of quality and trust over price, among the architect, structural engineer and steel sub-contractor. The legal and financial commitments were not jeopardised. Among the reported challenges, was the traditional role of the client: '*If I look back at other SC partnerships, the client also has to participate in it. We miss that in this project*' (Mechanical-Site Engineer-B). Regarding the performance of the SC, they reported that several informal aspects could be improved, such as even earlier discussions, and more frequent co-locations: '*All parties need to work regularly together, and everyone gives their input*' (Mechanical-Tender Manager-B).

In Case B, BIM was adopted because, given the project complexity, the partners '*did not dare to do the project in a traditional way*' (Project Architect-B). Concerning BIM implementation, most of the partners claimed that clearer scope about BIM was necessary, such as the levels of detail (LoD) and the function of the BIM coordinator, which was changed during the project from the architect's firm to an in training BIM-coordinator from the contractor's firm. Although '*this project, which was for the contractor one of the first times they used BIM, it was a little ad hoc*' (Structural Lead Engineer-B), it was more advanced than previous projects where they '*did not so do a super BIM model and had to improve a lot at the end, in this project it is better and (…) a lot of things have already been solved*' (Sub-contractor-Project Manager-B). The partners acknowledged their equal share to input, and the development of collective experience and knowledge, not only of the studied project but also from carrying experiences about '*BIM implementation from other contractors via the external BIM knowledge*' that their SC partners carried (Contractor-Project Manager-B). The suppliers were involved early in the project: '*We modelled the building permit application together with the sub-contractor and only after that the other suppliers modelled*' (Architect Modeller-B). Thus, the suppliers developed higher responsibility for their deliverables, since the controls were BIM-based and semi-automated, rather than contractor-lead manual checks. Some pressure in the scheduling and ambiguity among the various project phases were reported as well.

The narratives confirmed some of the formal aspects mentioned in the previous sub-section and specified a set of informal aspects that contributed to the performance of Cases A and B. Table 21 contains the collection and occurrences of recurring concepts across the narratives from observations, analyses, and reflections the interviewees made about the projects. The concepts are further classified as to BIM- or SCM-related respectively. The concepts with a different frequency between the two cases were further considered insightful for the performance of the SCs and the projects. Moreover, Table 21 reveals the differences in the perceptions of these concepts among the different disciplines involved in the two cases.

TABLE 21 Occurrences of recurring concepts throughout the narratives of the cases' interviewees.

Topic	Concepts	CASE A					CASE B					
		Architect	Structural	Mechanical	Contractor	Supplier	Architect	Structural	Mechanical	Contractor	Supplier	Sub-contractor
SCM	Legal commitments	13	7	9	16	7	10	12	7	12	4	13
	Equal partners-SCM	5	2	8	6	4	1	5	5	0	1	6
	Price-orientation	13	6	18	25	6	7	3	4	12	1	12
	Quality requirements	5	1	4	2	1	1	4	3	6	2	6
	Previous experiences	2	3	9	15	10	4	10	4	8	1	13
	Safe atmosphere	2	3	13	2	14	2	1	5	4	0	13
SCM and BIM	Early discussions	2	5	10	5	15	13	6	14	18	2	5
	Shared learning	3	8	10	35	13	9	11	7	18	3	16
	Informal communication	5	10	9	12	19	3	9	8	3	5	5
	Joint responsibility	10	3	6	11	11	12	5	4	6	0	9
	Partner selection	6	5	5	15	8	4	2	2	10	5	5
	Collaboration ('together')	8	8	3	6	10	4	18	6	19	8	17
	Clear scope	13	5	6	17	2	9	10	3	14	2	3
	Consensus	6	2	0	1	7	11	2	7	1	1	6
BIM	BIM clash controls	5	6	1	5	5	1	5	4	6	3	2
	BIM coordinator	5	3	0	3	3	1	3	1	4	3	1
	BIM protocol	4	1	0	12	1	1	1	0	0	0	0
	BIM agreements	21	13	1	19	1	2	6	2	10	2	1
	Common data environment	2	0	4	1	4	0	1	0	5	2	0
	Co-location	2	0	0	1	1	3	3	6	5	1	3
	Continuous phasing	5	1	6	7	4	3	0	2	4	1	2

§ 5.4.4 Two types of BIM-enabled SC partnerships

The two cases were selected not only based on their affinity to SCM and BIM adoption but also as polar cases with very distinct features. Their comparison could generate insights into configurations for BIM-based projects and SC partnerships. Table 21 summarises the recurring concepts from the case participants' reflections, and Table 22 contains the most divergent observations from the cases. Among the formal aspects that influenced the cases' performance, was the relation of certain key actors to the SC. The traditional client added to the unclear scope and changes in Case B, whereas the internal SC position of the architect contributed to the integration of the engineers and suppliers and encouraged informal communication. On the contrary, in Case A, the architect did not play a central role in the collaboration. In both cases, the actors felt pressure to meet the deadlines. The time pressure in Case A was caused by the late involvement of the suppliers, whereas in Case B they were early involved. Regarding the informal relations among the actors, Case B was engaged in co-locations and informal communications that bypassed the contractual relations. Finally, there has been no clear vision for a future collaboration with the partnership of Case A, while the SC of Case B has been already planning their next project. Overall, it could be assumed that Case A was more formal, e.g. transactional, contractual, and price-driven, whereas Case B was more informal, relational, and collaboration-driven.

TABLE 22 Summary of observations formal and informal relations in cases A and B.

ASPECT	CASE A	CASE B
Formal	The overall project planning was decided from the top management of the UAV-GC contract	The construction plan was decided in pull-planning sessions among the suppliers
	BIM competency was a factor of tender award	Cultural alignment was a SC selection criterion
	The BIM clash-sessions were held per building unit and discipline; many federated models	The BIM clash-sessions were held at a contingency level; only one federated model
Informal	The actors focused more on the project	The actors focused more on the SC partnership
	The BIM collaboration process was pre-defined	The BIM collaboration process was flexible
	The engineers never conferred with the suppliers	The communication extended across multiple tiers
	The BIM protocol was detailed but not followed	The BIM protocol included basic agreements
	Co-locations took place only to troubleshoot problems that emerged on site	Regular co-locations of the team were encouraged
	The use of informal communication channels was minimal and always through the contractor	The use of informal communication channels was highly encouraged across multiple tiers

§ 5.5 Discussion

§ 5.5.1 Formal and informal relations in BIM-enabled SC partnerships

Asymmetrical relations in BIM-enabled SC partnerships

The relation between the formal and informal aspects of BIM-enabled SC partnerships (RQ1) was asymmetrical: the formal contractual agreements do not correspond to the informal flows of communication and collaboration. The two studied cases jointly supported this. On the one hand, Case A had a sophisticated UAV-GC contract, which could instigate further SC integration, and various formal relations and preferred partners

(Figure 23), however, the communication was not extended across multiple tiers (Table 22). On the other hand, Case B concerned a few bipartite SC contracts and preferred partnerships stemming from the contractor (Figure 23), but surprisingly, the emphasis was placed on collaboration and on informal communication channels that bypassed the contractor (see the quotation of Project Architect-B) and were based on permanent contact persons across the involved firms (Table 22). The latter conforms with Bresnen and Marshall (2000, p. 235) who questioned whether partnering could be actively 'engineered' by simply applying contractual techniques, and claimed that exploring these inter-relations requires the analysis of both formal and informal aspects. The narratives of Case B implied a safe atmosphere (Table 21), and subsequently a shift towards 'high-involvement' relations in construction (Gadde & Dubois, 2010). The only indication of low integration in Case B was that the client's involvement was additionally desired (see the quotation of Mechanical-Site Engineer-B). Although both cases had long-term contracts, Case A was more based on formal relations, i.e. it was 'transactional', whereas Case B relied on equal partners' input to achieve consensus, instigate higher project quality (Table 21), and reach SC integration, i.e. it was 'relational' (Leuschner et al., 2013).

Whether the partnership was transactional or relational reflected on the chain's BIM implementation. Case A, which had more long-term contractual relations than Case B (Figure 23 and Table 20), focused more on selecting their SC partners based on their BIM competence (Table 21 and Table 22). On the contrary, in Case B not all strategic partners were BIM users and BIM adoption was considered a gradual shift in their practices, which was managed by frequent co-locations, denser collaboration, and consensus-seeking decision-making (Table 21 and Table 22). Therefore, whereas BIM becomes a prerequisite for the suppliers' selection (Mahamadu et al., 2014), the composition of the BIM chain depends on the either transactional or relational nature of the SC partnership is (see Table 22).

An unexpected finding was that in Case A, an asymmetry was also observed between the formal and informal relations of engineers and suppliers. The architect, mechanical engineer and supplier (supp2) were all directly tendered or preferred partners, and thus were not strategic for the chain (Figure 23). However, the supplier focused more on informal SCM concepts, e.g. previous experience, joint responsibility, and need to work collaboratively (Table 21), than the engineering firms. The engineers reflected more on the informal aspects of BIM implementation, e.g. having a clear scope, BIM-related LOD agreements, and impact of BIM implementation on project phasing. Whereas the sample is small, this could indicate a difference in the perception of BIM-enabled SC partnerships between engineers and suppliers that could originate from the longer history of partnerships among the suppliers' culture, rather than the engineering firms of the construction SC. The engineers were primarily interested in BIM and the suppliers in partnering.

§ 5.5.2 The impact of BIM-enabled SC partnering on the chain's performance

The formal aspects of the BIM-enabled SC partnerships, e.g. contracts and CDE use, proved to be crucial but not sufficient to manage the project complexity and improve its performance (RQ2). On the contrary, informal aspects of the BIM-enabled SC partnerships, such as early discussions, communication across multiple tiers, and co-location provided complementary structures to support the performance of the partnership and the project. Whereas both cases A and B had long-term contractual agreements, these formal aspects could not predicate the performance of the chain. In Case A, the contract type was more sophisticated and involved more actors, however, this was not sufficient to engage the whole chain. This could be potentially due to the weak role of the architect, who was external to the partnership. Thus, the partnership of Case A remained largely transactional and did not integrate further.

In Case B, earlier discussions took place (Table 21), and the suppliers were involved in the project after the Definitive Design phase (Figure 24 and Figure 25). The early discussions across multiple tiers – engineers and suppliers – increased the interactions among the project team and incited informal aspects of partnering. This is also consistent with the literature on the emergence of non-contractual relationships between suppliers and designers or engineers, which have been largely neglected in past research (Sariola & Martinsuo, 2016). The early involvement could be evidence of a shift where the suppliers would assume a more dominant, rather than reactive role in design (Nederveen et al., 2010). However, as the client was rarely included in the early discussions, the adversarial culture could not be avoided (El-Sheikh & Pryke, 2010). Whereas early actors' involvement has been deemed possible for BIM implementation (Eadie et al., 2013), an additional long-term SC partnership relation, and particularly relational- rather than transactional-orientated, could support BIM and encourage further SC integration.

Whereas BIM competency was a partner selection criterion for Case A, was apparently not sufficient for a successful BIM implementation (Figure 23, Table 21, and Table 22). In Case A, the acquired BIM knowledge was well circulated within the contractor's firm (see the quotation from Contractor-Design coordinator-A), but did not advance BIM knowledge across other firms of the SC partnership. This could be yet another indication that BIM implementation requires support from informal relations, beyond contracts, such as early discussions, frequent and strategically placed co-locations, and an inclination for shared learning within the partnership. For example, the frequent co-locations facilitated the integration of the BIM-enabled SC partnering. This practice took place in Case A after the start of the construction, when the partners were gathered once a week on-site for problem-solving. In Case B, the frequent co-locations supported the partners' informal communications and the BIM-based collaboration (Table 21 and Table 22). The fact that even more frequent co-locations were desired (see the quotation from Mechanical-Tender Manager-B), indicates a need to consciously align these co-location practices with BIM implementation.

Based on the empirical data from the case narratives a set of suggestions could be extracted to increase the understanding and fostering of the inter-organisational networks that develop within BIM-enabled SC partnerships:

- Participation of the client and the architect to the BIM-enabled SC partnership;
- Early involvement and discussions with the project suppliers;
- Frequent and wisely strategical co-locations among multiple tiers;
- Unanimous decisions about the BIM scope, protocol, standards, and CDE;
- Re-evaluation of the partnership scope, i.e. transactional versus relational;
- Use of shared BIM learning in addition to BIM-competency partner selection criteria within the SC partnership.

§ 5.5.3 Emerging functions and structures in BIM-enabled SC partnerships

The studied BIM-enabled SC partnerships identified several emerging functions and structures. The BIM managers and BIM coordinators (functions) were responsible for defining the BIM protocols and execution plans (structures) collectively together with the other disciplines and perform the federation of the segregate IFC models. These emerging functions can be categorised as more informal than formal. Whereas they used documents (structures) to define their agreements, their functions pertained more to informal partnering relations such as communication, previous common experience or shared learning (Table 21). The BIM coordinator and BIM manager roles were functions vaguely-defined across the cases. In Case A, there were both a firm-based BIM manager and a project-based BIM coordinator in the contractor's firm, whereas, in Case B, these roles were performed by a BIM coordinator in the architect's firm and an in-training BIM-coordinator in the contractor's firm. Undoubtedly the architect's model was the basis for the work of the other partners (Figure 24). However, the architect's firms had varying roles and responsibilities in Cases A and B, as to their contractual obligations and their actual input. This difference could later suggest a reconfigured SC partnership with more strategic actors in the 'BIM-chain', such as the architect, who could additionally facilitate the informal communication beyond their contractual obligations (see the quotation of Project Architect-B). In Case B, the architect was more proactive, held informal communication with partners from many tiers and was also responsible for integrating information from non-BIM using actors (Figure 24 and Table 22). These narratives also concur with the findings of Gu and London (2010) that the design disciplines were more keen to discuss collaborative culture than any other discipline. The architects' contribution to the BIM process extends beyond their technical tasks, includes more informal tasks, and is in direct contrast to the traditional perception of their role (Higgin & Jessop, 1965).

The BIM protocols were emerging flexible structures that pertained to operational and tactical decisions, and although very elaborate, did not include aspects, such as standards, codes, phasing, and responsibilities across the project lifecycle. Rezgui et al. (2013) stated that the BIM actions from the various disciplines at different lifecycle stages are crucial for the governance of the BIM process. For example, in Case A, the phasing was obscure because the actual timelines did not follow to the prescriptions set on the BIM protocol (Figure 24). This mismatch could be explained because the contractor alone prepared the BIM protocol and it was not unanimously accepted by the other partners (see the quotation of Contractor-Design coordinator-A). To this end, the flexible and high-level BIM protocol of Case B provided resilience to their BIM-chain. The BIM process was supported by extra informal communication means, such as emails, and phone calls. This confirmed the findings of Demian and Walters (2014) that the informal communications through email was irreplaceable (see the quotation of Project Architect-B). Thus, a balance of formal and informal structures is required to govern the BIM process.

Another unexpected finding of the study was the use of CDE that confirms the findings of Thorpe and Mead (2001) as to being a means to circumvent the traditional – or contractually-defined – communication channels, and simultaneously to support the storage and organisation the multi-disciplinary information required for BIM-based projects. The analysis of the CDE illustrated how the initial model of the architect, in Case A, is gradually reduced in size across the various multiple Design-related phases, by being gradually replaced by the models of the various other disciplines (Figure 25). In Case B, the architect was incorporating information from non-BIM using partners, and their model grew in the number of entities (Figure 25). Again, this is in direct contrast to the traditional perception of various actors' contribution (Higgin & Jessop, 1965), as in the BIM era, their contributions constantly change during the model development phases. The BIM protocol and the use of CDE would require additional informal aspects pertinent to partnering to be effective, such as seeking consensus, accepting joint responsibility, and having a long-term objective for shared learning (Table 21).

§ 5.5.4 Research implications

Theoretical contribution

Both tangible and intangible constructs from various data sources (contracts, CDE, interviews) were analysed to answer the research questions on the formal and informal relations in BIM-enabled SC partnerships. This combination aligns with debates about balancing the inductive and deductive thinking in SC research (Golicic et al., 2005), and particularly by examining both qualitative and quantitative data. Also as BIM implementation is a socio-technical issue, a mixed method was pursued. The formal relations were deduced from SNA, modelling, and quantitative data, and the informal relations were induced from the responses of the case participants to the interviews and qualitative data that enriched the quantitative data and analyses. After all, the insights into the involvement, division of work, and processes of the various actors could not have been obtained by interviews in a consistent manner. Simultaneously, the emergence of recurring constructs, such as trust, could not have been identified via analytical approaches and quantitative data. The contribution of this approach would be a set of new insights into SCM concepts, SNA methods, and the exploration of BIM implementation as an emergent phenomenon.

Therefore, whereas BIM has been considered an enabler for SC integration (CIC, 2011), its deployment has to be complemented with various formal and informal functions and structures. This study presented evidence on the combination of BIM implementation with SCM philosophy and provided insights into the formal and informal relations that affect the performance of the chains. After all, the performance of the supply chain has been found to drive the project performance (Mesa, Molenaar, & Alarcón, 2016). By means of case studies, SNA, and information modelling methods, the study analysed both formal and informal relations. To analyse the BIM-based information exchanges, the analysis of the CDE was selected as a tangible means to complement the contractual analysis via SNA, as BIM implementation is a dynamic process and cannot be fully captured by post-hoc data collection, which has so far been the norm in construction SNA. The CDE analyses show a promising way forward to explore and understand the BIM-based collaboration (Charalambous et al., 2013). Afterwards, the contractual and information analyses were combined to provide a comprehensive image of the BIM-enabled SC partnerships.

Research limitations

A research weakness is focusing on BIM-enabled SC partnerships only in the Netherlands. The Dutch construction market was a more relevant locale to test newly introduced innovations, such as BIM and extensive partnering, given that this market despite being smaller, has a high rate of BIM adoption, and there are possibilities for second-hand, or '*external*' BIM knowledge (see the quotation from Contractor-Project Manager-B). The overall instilled consensus-seeking culture of the Dutch construction firms (Dorée, 2004), could be considered apart from a research limitation, possibly a promising way forward for enriching BIM policies through the enrichment of BIM with SCM philosophy.

§ 5.6 Conclusions

Apart from providing evidence on BIM implementation from SC partnerships, the study recognised the conditions for combining SC partnering with BIM implementation. It analysed the formal and informal relations of two different BIM-enabled SC partnerships and how they affected the performance of the chain. *The construction networks were found asymmetric as to the relation between the formal and informal structures and processes that the engineers and suppliers used for engaging in and facilitating BIM implementation* (answer to RQ#4). *The highly sophisticated contracts and the selection of innovative BIM-competent partners were not sufficient to instigate additional informal relations among the SC partnerships. The integration depended on whether the partnership was transactional (Case A) or relational (Case B).* Overall, the innovative and sophisticated BIM-based processes from Case A would additionally require more informal aspects, such as the interest towards seeking consensus, collocating, accepting joint responsibility, and inclination for shared learning (Table 21). Following the relational orientation of Case B, the SC partnerships could further support BIM implementation, by emphasising more on informal structures and early discussions and communication across multiple tiers. The integration also depended on the composition of the strategic or internal partnership, and particularly on the participation or not of the client and the architect. The architect was a vital link of the BIM-chain for BIM implementation in the SC partnership, given that they were responsible for creating the initial architectural BIM model that was further distributed to the other disciplines. Accordingly, some recommendations for achieving integration, including the SC composition and the collaborative structure were extracted.

Among the unexpected findings of the study were emerging BIM-related functions in the firms of the architects and the contractors, for the deployment of innovative and integrative technologies, e.g. online collaboration via CDE (Figure 25). After a comprehensive analysis of SNA studies in construction (Table 17), the quantitative analysis of the CDE was chosen as a complementary method to capture the digital information exchanges of the ON across time. These digital information exchanges through the CDE provided a more pragmatic image of the partnership, after comparing them to the contractual centralities of the actors. To that extent, additional insights into both the digital and contractual relations of the construction networks were extracted (Figure 23). Whereas contractually the contractors were the most prominent actors, in the BIM era the architects are stepping up to play a dynamic role in the BIM-based collaboration and informal communication. Accordingly, a combination of BIM-savviness and keenness to diffuse BIM knowledge across the SC partnership would be a promising way forward for further integration of design and construction and diffusion of both BIM practices and SCM philosophy. Analysing the organisational complexities of BIM-enabled SC partnerships could contribute to further developing SCM concepts as well as ameliorating the utilisation of BIM in multi-disciplinary environments. Further research could include data collection and ON analysis from additional aspects of communication, e.g. the download CDE interactions, and ethnographic observations from emails and phone calls. Subsequently, a complete image of the formal and informal channels to support a BIM-based project would be explored. Additionally, cross-cultural case selection would shed more light on the complex socio-technical phenomenon of BIM-enabled partnering, which is increasingly becoming global.

6 Intra- and inter-organisational relations[8]

Chapter summary

After the empirical (Chapter 3), conceptual (Chapter 4), and pragmatic (Chapter 5) explorations of the emergent phenomenon of BIM-enabled SC partnering, an additional study for the identification of the emerging intra- and inter-organisational relations took place. During the explorations of Chapters 4 and 5, additional insights were obtained as to the intra-organisational level of the research. Therefore, it was deemed necessary to undertake an exploration of the intra-organisational level of analysis as well. Whereas the Unit of Analysis of this dissertation has been the firm – or organisation – the intra-organisational level of analysis proved to play a crucial role in the adoption and implementation of BIM and SCM, for the collaboration, coordination, and potential integration of the actors. Therefore, the two polar (extreme) cases that were analysed in Chapter 5 were revisited and re-analysed as to their SCM and BIM from an inter- and intra-organisational perspective. From the P/P/A frameworkof Chapter 2, in this chapter, the emphasis was given on the analysis of only the actors and their inter-relations.

This chapter focuses on the impact of BIM on the intra- and inter-organisational relations of BIM-enabled SC partnerships (RQ#5). A prominent theoretical framework of past literature on the implementation of SC partnerships was selected and deployed as an analytic framework for the narratives of the case participant of the two cases. This framework was chosen, because it presented similarities to the constructs emerged in the 'Reflection' phase analysis of the two polar cases in Chapter 5 (see Table 21*). Subsequently, the tentative findings from Chapter 5, as to the transactional or relational orientation of the two cases, were validated. Afterwards, key intra-organisational parameters for further integrating the BIM-enabled SC partnerships were identified. Overall, the emerging intra- and inter-organisational relations were found contrasting due to internal tactical and strategic decisions of the involved firms in the SC. Therefore, probably, an additional intra-organisational alignment has to take place prior to the inter-organisational alignment of firms that wish to engage in BIM-enabled SC partnering.*

8 This chapter is largely based on a paper under first revision, after invitation to submit to a Special issue on "Using building information: organisational and policy implications of the digitisation of buildings" (Papadonikolaki et al., In 1st Revision).

§ 6.1 Introduction

The AEC industry has been deemed disintegrated, i.e. displaying a lack of integration, regarding its processes (Howard et al., 1989), and fragmented, i.e. consisting of various small firms of involved multi-disciplinary actors (Nam & Tatum, 1992). To counterbalance this disintegration and fragmentation, the construction industry has resorted to integrated solutions for design practices and project teams. The digitisation of building information through BIM could improve the project performance (Bryde et al., 2013), collaboration, and coordination (Dossick & Neff, 2010). BIM impacts not only the design and construction processes of AEC but also the organisational structures. Sebastian (2011b) acknowledged that the various roles radically change because of BIM. Whereas these changing roles appear highly interdependent (Jaradat, Whyte, & Luck, 2013), there is a lack of understanding about the impact of BIM on already integrated inter-organisational settings, such as SC partnerships.

The adoption and implementation of BIM have been previously associated with partnering structures, which are usually client- or demand-driven, such as the Public Private Partnerships (PPP) (Porwal & Hewage, 2013; Love, Liu, Matthews, Sing, & Smith, 2015). Such partnerships have little effect on the actual project team coordination and hardly extend across multiple tiers. On the contrary, the concept of SCM introduces the potential for deeper integration across tiers, from a relational perspective (London & Kenley, 2001). Given that the concept of SCM, which has emanated from logistical and operational considerations, has allowed for numerous interpretations, in this study it is approached through the lens of SC partnerships, which imply contractual relations across many tiers (Lambert et al., 1996). The SC partnerships are constellations of multiple 'dyadic' relations among companies that aim to reduce their inter-organisational interfaces, across projects, and beyond organisational barriers, by intensifying their communication, aligning their planning, deploying joint operations and inculcating mutual trust (Lambert et al., 1996). Studing the phenomenon of BIM-enabled SC partnerships in the Netherlands could provide useful insights into the relations of partnering and BIM and the derived actors' roles.

The aim of the paper is to explore the compatibilities and incompatibilities of SC partnerships and BIM. The focus is on identifying the interplay of SC partnership and BIM implementation and exploring the transforming functions of key actors of the built environment, e.g. contractor, architects, engineers, and suppliers. The study aims to explore:

- The emerging inter-organisational relations in BIM-enabled SC partnerships;
- The intra-organisational parameters for further integrating BIM-enabled SC partnerships.

The next section reviews the interplay of BIM and SC partnerships, in theory, establishes the associated gap, and underpins the research (section § 6.2). The following two sections describe the methodology to facilitate the study by empirical explorations (section § 6.3) and present the research findings in detail (section § 6.4). The ensuing section mobilises the findings of the interplay and emerging functions from BIM-enabled SC partnerships, against relevant literature (section § 6.5). The concluding section summarises the findings and presents the implications for construction practitioners (section § 6.6).

§ 6.2 Background, related research, and research gap

§ 6.2.1 SC partnerships and integration

SCM is the management of a set of multiple firms "directly involved in the upstream and downstream flows of products, services, finances, and information from a source to a customer" (Mentzer et al., 2001). Christopher (1992) refers to this set of firms as 'network'. The concept of SCM and SC partnering have been found to be synonymous in the construction industry (Fernie & Thorpe, 2007). As the concepts of SCM and SC partnerships have emerged from efforts to attain performance in logistics, there "has been much debate about distinguishing" logistics from SCM (London & Kenley, 2001). For example, in relevant literature from the UK, the prevalent view is that the firms continue competing on price despite the partnering (Fernie & Tennant, 2013) and that the partnering requires more than pricing formulae to be meaningful (Bresnen & Marshall, 2000). However, longitudinal studies on supplier development activities, such as training, technological support and performance evaluation reveal a direct relation between SCM and consistent project performance (Gosling et al., 2015). Evidence from other sectors indicates that SCM and SC partnerships could pertain to a more relational view. Christopher (1992; 2011, p. 217) viewed SCM as *network* management and anticipates major transformations in businesses, by shifting the emphasis from inventories to information flows, from financial transactions to inter-firm relationships, from functional to processual orientation and from stand-alone competition to network rivalry. To achieve 'high-involvement' partnerships (Gadde & Dubois, 2010) and overcome the barriers of short-term price-driven construction relations, emphasing on scope, joint vision, and long-term partnering is essential.

As there are numerous different classifications of SCM and SC partnerships, e.g. Lambert et al. (1996), Tan (2001), and Min & Mentzer (2004), this study will focus on the motives and the deployment of the SC partnerships. Mentzer et al. (2001)

differentiated between SC orientation and SCM, considering the former as a broader strategic prerequisite that the firms involved in SCM have to possess. Mentzer et al. (2001) also extracted from past literature certain activities as necessary for successful implementation of SCM philosophy: integrated behaviour, mutual information sharing, mutual risks and rewards sharing, cooperation, same goals, process integration, and long-term relationships. Tan (2001) likewise described the cultural change, trust, communication and information sharing across multiple tiers, suppliers' development, and sharing common goals as key drivers for SCM. Lambert et al. (1996) proposed a framework for justifying and implementing SC partnerships that consist of "planning, joint operating controls, communications, risk and reward sharing, trust and commitment, contract style, scope and investment as joint activities" (components) for SC partnerships. These SC partnerships were formed by "compelling reasons to partner" (drivers), such as cost, market and stability advantages, and characteristics of the firms that could help or hinder the partnership development process (facilitators), such as corporate compatibility, managerial philosophy, mutuality, and relational symmetry (Lambert et al., 1996). Apparently, there is an overlap among these frameworks. Lambert's et al. (1996) framework was further validated in a longitudinal study of twenty partnerships, and it was concluded how the SC partnership "can be an important aspect of successful SCM" (Lambert, Knemeyer, & Gardner, 2004).

Integration is another popular concept in SCM research. Vrijhoef (2011) considered SC integration as the result of intensive SCM in the areas of productivity, market position, building product quality, and team collectivism. The lack of integration in AEC is a persistent problem across its lifecycle and involved actors (Howard et al., 1989; Nam & Tatum, 1992). Integration can be considered pertinent to both processes and actors, and particularly regarding the latter, in the form of collaboration across tiers (Dulaimi et al., 2002). Dulaimi et al. (2002) provided evidence that strategies such as early involvement, risk and reward sharing, joint operations across firms, investment in IT and DB procurement methods increase integration. Accordingly, there is a relation between innovative management philosophies, such as SC partnerships, adoption of IT, such as BIM, and procurement methods for integrating the AEC.

§ 6.2.2 Partnerships and BIM

Whereas BIM research has proliferated in the last years in practice and academia, there is still a lot of ambiguity about how to fully reap its benefits via various procurement routes and partnerships. BIM is considered a "multifunctional set of instrumentalities for specific purposes that will increasingly be integrated" (Miettinen & Paavola, 2014) and affects various actors across the AEC lifecycle. Eastman et al. (2008) advice that DB procurement "may provide an excellent opportunity to exploit BIM technology because a single entity is responsible for design and construction", as it is more cost-efficient and integrated in time than Design-Bid-Build (DBB). Holzer (2015) conducted an analysis of the opportunities for BIM under various procurement methods and concluded that IPD is contractually appropriate, for full BIM implementation, although it is not applicable to every market (Sebastian, 2011, Holzer, 2015). Accordingly, Kent & Becerik-Gerber (2010) corroborate that the projects with BIM and IPD combination "remain relatively small". Whereas all procurement routes could potentially support BIM (Eastman et al., 2008), the DBB further disintegrates Design and Construction, whereas the DB discourages the client's involvement in Design and Construction phases (Sebastian, 2011a). Therefore the project scope and chosen procurement approach influence the involvement of the various key actors, and further affect the integration of the SC.

The adoption and implementation of BIM have also been associated with partnering structures, in the form of Public Private Partnerships (PPP), which could counterbalance the lack of client's involvement in Design and Construction (Love et al., 2015). The PPP partnerships are greatly supported by National mandates and institutional mechanisms responsible for the diffusion of BIM. However, these efforts pertain to the demand, rather than the supply side of the SC and have little influence on the actors involved in Design and Construction. In a similar spirit, Porwal and Hewage (2013) focused on publicly-funded construction projects, perceive the inter-relations of BIM and partnering from the demand side, and claim that "maturity and adoption of BIM depend mainly on the client or the owner in construction". This study focuses on the supply side of the SC, to explore the compatibilities and incompatibilities of BIM and partnering across multiple tiers, i.e. contractors, engineers, and suppliers, from a 'bottom-up' angle.

From a strategic perspective, Deshpande (2012) associated the long-term partnering relationships, with supporting concurrent engineering and strategic purchasing functions for both the demand and supply side of the chain. On the supply side, there is much evidence in literature of how BIM could improve the coordination of Mechanical, Engineering and Plumbing (MEP) engineering tasks, under conditions such as prior BIM experience and early joint decision-making (Dossick & Neff, 2010; Wang & Leite, 2014; Ahn et al., 2015). The BIM-based design coordination process usually contains elements of concurrent engineering (Lee, 2014), which in turn could potentially intensify the above activities of the SC partnerships. In particular, Lambert's et al. (1996) SC components such as joint planning and operations, intensive communication, risk and reward sharing, trust and commitment could be potentially enablers for BIM implementation. This chapter analyses the key *RQ#5: How does BIM impact the intra- and inter-organisational relations of BIM-enabled SC partnerships?* It further divides it into two sub-questions and explores:

- How does BIM impact the inter-organisational relations of BIM-enabled SC partnerships?
- What are the intra-organisational parameters that contribute to the integration of BIM-enabled SC partnerships?

§ 6.3 Methodology

§ 6.3.1 Methodological rationale

Research rationale

To respond to the above research questions and explore the perceptions of the various actors about the BIM-enabled SC partnerships, case study methods were selected, because they provide an in-depth analysis of the phenomenon in its "real-life context" (Yin,1984). The combination of SC partnerships and BIM were studied in its "natural setting", to potentially provide insights into other inter-organisational BIM settings (Benbasat et al., 1987). The cases were exploratory. However, Bengtsson and Hertting (2014) claim that the findings from cases could be generalised when "expectations about similar patterns (...) in similar contexts" take place, i.e. similar settings of BIM-enabled SC partnering.

The research setting was in the Netherlands where both concepts of BIM and SCM flourish. SCM and SC partnerships in the Dutch AEC have been popular approaches to replace the traditional tendering processes (Vrijhoef, 2011). The SC partnerships use short documents to prescribe the inter-firm relations, i.e. SC 'framework agreements' (Pryke, 2002). These SC partnerships were based on long-standing pre-existing inter-firm relations that aim at increasing process and product quality. The implementation of BIM in the Netherlands has been particularly balanced by presenting a proportional mix of mandates and suggestive documents (Kassem et al., 2015). The Dutch AEC has been quite proactive in BIM-related initiatives, for example in developing BIM assessment tools after popular demand of AEC firms (Sebastian & Berlo, 2010). The latter is evidence that the Netherlands is an appropriate research setting also for cultural reasons, by displaying a ubiquitous consensus-seeking, '*poldermodel*' culture that fosters closer collaboration among firms. Winch (2002, p. 25) described the Dutch construction industry as a Corporatist type System where the construction actors are keen to negotiate and seek consensus to reduce costs and risks. This consensus-seeking culture would be helpful to investigate the phenomenon, given that the AEC, lately, also seeks ways to increase collaboration and integration.

Case study selection

The empirical context of the study included two networks of actors organised in SC partnerships that developed two BIM-based projects. The partnerships not only provided a structured setting for the study but also enabled the data collection process by unimpeded access to information. This open setting served as a 'bottom-up' approach to BIM implementation. After all, many national mandates, e.g. the Egan report in the UK have been envisaging SC integration, as a result of close collaboration.

Two cases were analysed, to examine the inter-organisational relations of BIM-enabled SC partnerships. The cases were snapshots of 'interaction episodes' of the two SCs, embedded in their time and space context (Gadde & Dubois, 2010). They were selected from a larger pool of BIM-using SC partnerships, and were representative of this phenomenon because:

- Large, medium or small firm sizes were involved;
- They used similar SC frameworks agreements and had a long-term scope.
- They used open standards, i.e. Industry Foundation Classes (IFC), which allowed the SC partners to use various BIM software applications;
- They used Common Data Environments (CDE) to exchange information.

Despite the similarities, the two cases were *polar* cases, because they had diverse partnering goals; case B was a much long-standing partnership. According to Eisenhardt and Graebner (2007), the polar case sampling could lead to distinct patterns on the phenomenon under study. Through their differences, the cases could generate insights into a spectrum of BIM-enabled SC partnerships and support a potential generalisation of the results.

§ 6.3.2 Case study design

The focus of the study was at the inter-organisational level, and particularly the relations of the various multi-disciplinary firms. The case study design did not concentrate on one "focal" firm of the SC partnership, instead devoted about equal time to all partners. The cases focused on interviews and not on documents or contracts, to emphasise on the incongruent actors' interpretations. Whereas the Unit of Analysis (UoA) was the individual firm, to ensure a grounded understanding and avoid biases (Eisenhardt & Graebner, 2007) employees from various hierarchical levels were interviewed, from top management to modellers. Within engineering firms, usually, three functions were interviewed: the project/tender manager, the lead engineer, and the modeller. In smaller firms, these functions were combined in one.

The interviews with various functions per firm contributed to acquiring additional intra-organisational insights into emerging functions within the AEC firms. Table 23 describes these interviewees.

TABLE 23 Interviewed firms and employees for Cases A and B.

CASE A			CASE B		
Firm	Role/position	BIM user	Firm	Role/position	BIM user
Contractor	Site Engineer	x	Contractor	Site Engineer	x
Contractor	BIM Manager	x	Architect	Project Architect	x
Contractor	Design Coordinator	x	Architect	BIM Modeller	x
Architect	Project Architect		Structural Engineer	Lead Engineer	x
Architect	BIM Modeller	x	MEP Engineers	Tender Manager	
Structural Engineer	Director		MEP Engineers	Site Engineer	x
Structural Engineer	BIM Modeller	x	MEP Engineers	BIM Modeller	x
Mechanical Engineer	Project Leader	x	Sub-contractor	Project Leader	
Supplier (Supp2)	Tender Manager		Supplier B1	Director	
Supplier (Supp2)	BIM Engineer	x	Supplier B1	BIM Modeller	x

The interviews were semi-structured and had consistent preparation and data handling. Before the interviews, all interviewees had the same information about the study. The questions were about the motivation and implementation of BIM-enabled SC partnership, and the interviewees' functions. Question hand-outs were administered at the start of the interview. The interviewees conversed in Dutch. The interviews were recorded with permission to aid the transcription and translation by research assistants. The transcripts were analysed with qualitative analysis software, using free codes, and frequency and co-occurrence metrics. The firms welcomed the use of their input for research but desired anonymity.

§ 6.4 Data analysis and findings

Case description

Case study A was a multi-functional building complex, which consisted of three buildings with 255 residential units, offices and commercial spaces, located next to a canal. The contractor, client, heating and energy firms, and the facility manager formed a SC partnership, in the form of a so-called UAV-GC (In English: Uniform

Administrative Requirements for Integrated Contracts) contract for 20 years, which is similar but involves more explicit financial agreements than a Design-Build-Maintain (DBM) contract. A UAV-GC contract generates information that can be re-used across projects and has a long-term scope. BIM was applied from the Preliminary Design until Pre-construction and will be used for the maintenance. Case study B concerns a housing tower, with 83 housing units over a pre-existing building, and high technical complexity. The contractor had SC contracts with the architect, structural engineer, steel sub-contractor and suppliers, e.g. windows, cladding, roof. BIM was applied from the Initiation until Construction, and 'as-built' BIM will be delivered. The main difference between the cases was the longevity of the SC partnership, as Case A was a new, but Case B was a long-standing partnership.

Both partnerships had long-term relations. However, the contractual relations were manifested differently throughout the interviewees' narratives. The components of the framework by Lambert et al. (1996) was used to (a) first, present the dissimilarities and complementarities of two polar cases and (b) second, to focus on the compatibilities of BIM and SCM. Table 24 compares the co-occurrences of the SC partnership components in the two cases, to identify relations across the SC constructs. Table 25 presents the SC partnership components across the narratives of the various actors throughout the cases. The narratives of case A was focused more on the contractual means to support their financial risks and rewards, whereas case B emphasised more on joint scope and the high trust throughout the SC partnership. Table 24 and Table 25 are lightly colour-coded to aid the interpretation about the various concepts.

TABLE 24 Co-occurrences of the SC partnership components from Lambert et al. (1996) in the cases.

SC PARTNERSHIP COMPONENTS	CASE A								CASE B							
	Planning	Joint operating controls	Communications	Risk/reward sharing	Trust and commitment	Contract style	Scope	Investment	Planning	Joint operating controls	Communications	Risk/reward sharing	Trust and commitment	Contract style	Scope	Investment
Planning	0	16	4	2	0	1	3	0	0	9	7	2	1	1	11	1
Joint operating controls	16	0	27	3	4	0	6	0	9	0	35	2	5	2	4	1
Communications	4	27	0	3	13	7	6	2	7	35	0	7	12	3	4	3
Risk/reward sharing	2	3	3	0	5	8	5	1	2	2	7	0	8	5	0	0
Trust and commitment	0	4	13	5	0	6	4	0	1	5	12	8	0	5	3	0
Contract style	1	0	7	8	6	0	11	0	1	2	3	5	5	0	4	0
Scope	3	6	6	5	4	11	0	2	11	4	4	0	3	4	0	0
Investment	0	0	2	1	0	0	2	0	1	1	3	0	0	0	0	0

TABLE 25 The presence of the SC partnership components from Lambert et al. (1996) across cases and actors.

SC PARTNERSHIP COMPONENTS DISCUSSED IN THE CONTEXT OF THE BIM-ENABLED SC PARTNERSHIP	CASE A					CASE B					
	Architect	Str. Eng.	Contractor	Mechanical Eng.	Supplier	Architect	Str. Eng.	Contractor	Sub-contractor	MEP	Supplier
Planning	6	0	8	5	7	7	3	5	8	10	0
Joint operating controls	9	8	21	9	12	9	12	11	13	15	7
Communications	12	21	18	12	18	15	17	14	14	27	9
Risk/reward sharing	9	3	20	8	6	6	4	5	13	7	1
Trust and commitment	2	9	10	6	9	5	6	9	20	11	1
Contract style	8	5	33	9	11	6	9	4	12	8	3
Scope	2	4	19	4	7	6	9	6	3	6	1
Investment	5	6	6	3	3	2	6	6	7	5	6

Case analysis

Components of SC partnerships and BIM

In case A, the data from Table 24 suggested that there were three main groups of topics discussed around the interplay of BIM and the SC partnering: contracts, operations, and communication. First, the SC components of *Scope, Contract style, Investment* and *Risk/reward sharing* co-occurred with strategic decisions about BIM. For the contractor: '*BIM was simply an obligation from the client*' (Contractor-Design coordinator). Likewise, the partners admitted that *'if the contractor does not ask BIM we do not do it'* (Structural engineer-BIM modeller). Simultaneously, whereas their contractual relations to the SC partnership were clearly defined, the BIM-related agreements and scope were vague: *'if you see the BIM protocol that we made there at the beginning of the project, it had not been regulated (...). Thus, the responsibilities and role partitioning had been not yet fixed'* (Contractor-Design coordinator). Regarding the strategic trade-offs between the adoption of BIM and SC partnering the contractor admitted that *'adopting a BIM strategy is less risky cost-wisely than adopting a SCM contractual strategy '(Contractor-Design coordinator).*

Second, the concepts of *Planning* and *Joint operating controls were* co-occurring with the discussions about BIM implementation. The partners were struggling to align the planning and joint project operations to BIM implementation. The contractor stated that *'if you have a BIM project you must have in fact firstly a design in BIM, and then your subcontractors would develop (their work) in BIM'* (Contractor-Design coordinator), whereas the mechanical engineer admitted that *'the design was not finished yet (...) but we just needed to build because we had to meet the schedule'* (Mechanical engineer-Project *l*eader). However, they managed to coordinate their activities despite the time pressure, by compartmentalising the problems arising: '*It depends a bit on what needs to be changed and which party is responsible for adapting. (…) It can take up to two weeks before the specific issue is completely processed*' (Architect-All-around architect).

Third, the concepts of *Communications* and *Trust and commitment* co-occurred with BIM. There were formal and informal communications beyond the contractual relations: '*I can directly contact the engineers but then inform the contractor' (Architect-All-around architect)* and '*I think the contractor has always expected us that we go to find out among ourselves and that we contact the architect to sort things out*' (Structural engineer-BIM modeller). The communication also extended beyond the project: '*the partners have asked us to guide and educate them (…). Our BIM knowledge has increased considerably, and we may spend time with our subcontractors to solve BIM export problems physically together*' (Contractor-Design coordinator). From the interactions among the firms, the BIM implementation was supported, particularly if the partners were involved earlier: '*We need to have permanent contact persons in the partners' firms, so this is where the SC partnership and BIM are intertwined. I think that you cannot do good BIM without the SC partnership* (Supplier-BIM modeller).

In case B, the interplay of BIM and the SC partnering was clustered around contracts, scope, and joint operations. First, the components of *Contract style* and *Risk/reward sharing* co-occurred with BIM adoption. For most firms in case B, SC partnering had a long history; they '*have become quite developed by this, only back then it was called differently*' (MEP Engineers-Site Engineer) and they '*are quite used to enter into a Supply Chain partnership*' (MEP Engineers-Tender Manager). Because of BIM, their business transactions evolved: '*We were used to simple tendering assignments but not anymore. Nowadays it's very easy to receive the BIM model and find it out. The BIM model is like what the tender proposal was back then*' (Sub-contractor-Project Leader). Their risk-sharing structure remained the same, whereas the project briefing process evolved with BIM.

Second, the SC concepts of *Planning* and *Scope* frequently co-occurred with BIM. The interviewees were concerned about the relation between the scope of the partnership and the project and how the planning was influenced by BIM, e.g. they had '*agreed in advance at which stage what information was going to be applied (…) to connect with the sub-contractors*' (Contractor-Site Engineer). With BIM, they could align the project's scope and '*get earlier insights into where the bottlenecks really are in the process. So the forward thinking is far more important in the BIM process*' (Architect-Project Architect). The concepts of *Planning* and *Scope* were also connected to the discussions about Level of Detail: '*It's important that you have clear goals in advance; if you would later use the BIM model to manage the building or not. So the level at which you make that model, it must be agreed well in advance*' (Structural Engineer).

Third, the concepts of *Communications, Joint operating controls,* and *Investment* co-occurred with discussions about BIM. The BIM-based operations of the partners were combined with co-locations: *'Sometimes it's better just to sit jointly at the table because of the non-verbal communication'* (MEP Engineers-Site Engineer). Their communication was also very open, as a result of the pre-existing relations: *'in partnership we do not always have to agree with each other'* (Sub-contractor-Project Leader). However, a shift had to take place while investing in BIM, given that *'it is very difficult for people because they have to think outside their comfort zone, that they are so used to it for years (...). With the new communication possibilities of BIM, it's easier to exchange information'* (Contractor-Site Engineer) and therefore coordinate the SC collaboration and the project. They were also engaged in early discussions: *'we now work with each other at an early stage in the process (...) and that's actually a whole mentality change'* (Structural Engineer).

Key Actors in BIM-enabled SC partnerships

Whereas the two cases displayed different approaches to the development and implementation of the BIM-enabled SC partnerships, no major mismatches were observed among the actors of two cases (Table 25). Overall, in Case A the contractor was more dominant in the functions such as *planning*, *communications*, and *joint operating controls*. In case B, these considerations were equally shared across all actors. In both cases, the contractor held the SC contracts with the other partners. The contractor firm was seen as the *'spider in the web'* (Case B-MEP Engineers-Site Engineer) who might have had *'some yearly contracts but the larger part was bought traditionally'* (Case A-Contractor-Design coordinator). For both contractors, it was decided that *'all projects would be in principle in BIM because that is the future' (Case A-Contractor-Design coordinator)*. To support BIM implementation, the contractors were responsible for ensuring the Joint operating controls, by facilitating the co-locations. They spent *'time on the subcontractors to solve BIM export problems physically together'* (Case A-Contractor-Design coordinator), or *'sit down together in an IT-prepared space, everyone with their own laptop (...) to do their own thing so we can have design sessions together easily'* (Case A-Contractor-Site Engineer). They also retained and managed the communications over the Common Data Environment (CDE): *'they have always said 'hey there's a new model and that you should download just because it also affects you'* (Case A-Supplier-BIM modeller).

In both cases, the Architects were responsible for delivering the initial model of the project, e.g.: '*you will draw based on what was supplied the architect*' (Case B-MEP Engineers-Site Engineer) and '*we see the model of the architect as form and space within which we must operate*' (Case B-Contractor-Site Engineer). Their additional role in the partnership was to facilitate the communications across the partners: '*our real role is good collaboration and making clear agreements about it. That sounds crazy to be our only role*' (Case B-Architect-Project Architect). However, the communications in case B were from the Architect across multiple tiers, e.g.: *'in that sense the communication goes all ways. It is not only that we give information, but we also need a lot of the suppliers'* (Case B-Architect-Project Architect), whereas, in case A, the supplier stated: '*we did not have contact with the architect. We did have a lot to do with the other suppliers though'* (Case A-Supplier-BIM modeller).

The Structural and Mechanical engineers of the cases assigned less emphasis on *communications*, and focused on *planning*, and *joint operating controls* instead. No significant change was reported about their function in BIM-enabled SC partnership. In case A, the construction began before the design was finished and this placed a lot of pressure on the partners. On the other hand, in case B, the time pressure was associated with the commercial decisions of the top management: '*the commercial guys, who sit on the second floor above, sell a very nice project to a customer, then we will start a fixed date and go. And that is for us, of course, enormous time pressure, to make the right decisions*' (Case B-Contractor-Site Engineer). To rectify these challenges, the sub-contractors and suppliers associated the *planning*, and *joint operating controls* to *scope*: '*we have more expectations when we look at the work earlier, and we judge accordingly*' (Case A-Supplier-Tender Manager). Both the engineers and suppliers devoted a large part of their narratives to associate *Risk/reward sharing* to *scope* and *planning* and particularly by reflecting on the impact that their earlier involvement has to the process: '*And now we try with BIM to shape the process earlier together. To then have fewer errors in the process*' (Case B-Structural Engineer) and '*we have first to make a design together and then to go and see what it costs*' (Case B-Sub-contractor-Project leader).

From the above narratives, the various actors differentiate functionally in the BIM-enabled SC partnerships. Namely, the contractors acted as the coordinators of the joint operations and the architects as the initiators of the BIM model and enablers of communication among the SC. The alignment of the rest of the engineers and suppliers to the collaboration and coordination structures was influential in the projects.

§ 6.5 Discussion

§ 6.5.1 Inter-organisational relations in BIM-enabled SC partnerships

The two cases displayed similarities as to the drivers and facilitators and dissimilarities as to the components of partnering. For both cases, the shared history of past projects was an internal 'cultural' driver to deepen their inter-firm relations (see the cases' narratives on *Trust and commitment* and *Contract style*). Moreover, both cases displayed evidence that the adoption of digital technologies, such as BIM, was an external (environmental) factor that facilitated the SC partnership, given that the client required BIM as a contractual requirement. After all, the clients' project delivery decisions can affect and outline the SC relationships (Mesa et al., 2016). Other studies have also corroborated that BIM becomes a partner selection criterion (Mahamadu et al., 2014). Thus, for both internal (drivers) and external (facilitators) reasons, BIM and SC partnering were compatible.

Despite the similarities, the cases presented two contrasting types of BIM-enabled SC partnerships. From the co-occurrences of concepts and narratives (Table 24), there were two main mismatches, as to Lambert's et al. (1996) SC partnership components of *Planning* and *Communications*. For case A, the discussions about *Planning* were more associated to *Joint operating controls* as opposed to case B, where *Planning* was discussed under the lens of *the* project and SC *Scope*. This observation relates to discussions over the strategic versus operational perspectives of SCM and to what extend the SC visions are diffused on the work floor (Tan, Kannan, & Handfield, 1998; Green et al., 2005). Accordingly, case A viewed *Planning* as a result of the joint operations (operational SCM perspective) and the narratives were focused on efficiency improvement, which is the perspective of SCM that "dominates the literature" (Green et al., 2005). Whereas, in case B, *Planning* was strongly related to *Scope* (strategic SCM perspective) and conceptually linked to commercial decisions and "dynamics of competitive positioning" (Green et al., 2005). Based on the above, the planning was associated to either the operational (case A) or the strategic (Case B) of the SC partnership. It could then be deduced that Case A was more operational, whereas Case B more strategic.

Another disparity between the cases pertains to *Communications*. In case A, the communications was seen as a consequence of *Trust* as opposed to the co-occurring concepts in case B of *Joint operating controls,* and *Communications* (see the cases' narratives on *Communications)*. This dissimilarity concurs with the claims of Bresnen and Marshall (2000) that "there is a division between those who see partnering as an informal and organic development and those who regard it as something more formal that can be actively engineered", which could resonate with the narratives from case B (informal) and case A (formal) respectively. For Green et al. (2005), trust is considered a prerequisite of mutually interdependent relationships (Case A), while the SC partners of case B worked proactively in joint operations to build trust, beyond their organisational and contractual boundaries (Case B). For both cases, an unexpected finding was the use of joint investment from the partnerships. Contrary to the framework from Lambert et al. (1996), the firms focused on investment in time for joint BIM learning, rather than *joint investment* in technology or personnel.

§ 6.5.2 Intra-organisational parameters of BIM-enabled SC partnerships

The functions of the main actors in the BIM-enabled SC partnerships present implications as to their emerged inter- and intra-firm relations from investing or adopting BIM. The involvement of key actors in BIM-enabled SC partnerships, such as the contractors, engineers, and suppliers will be discussed separately. Ackoff (1970) and Mintzberg et al. (1996) divided corporate planning into strategic, tactical, and operational levels and address the danger of detaching senior management from tactical decisions and work floor operations (Mintzberg et al., 1996).The next paragraphs discuss this detachment.

The contractors' firms were the most homogenous and consistent actors across the cases. They provided the CDE for online information exchange infrastructure, the '*IT prepared space*' for co-locations and design coordination, occasionally offered BIM training to their partners (Case A) and also featured dedicated BIM departments (Ahn et al., 2015). Simultaneously, through their commercial and strategic decisions they influenced the BIM adoption and investment of their partners, which is evidence against the claims of Porwal and Hewage (2013) that BIM maturity and adoption depend mainly on the construction clients. Likewise, whereas there was evidence of 'top management support' for SCM (Mentzer et al., 2001), there was apparently an incongruence in understanding and planning the BIM-based projects between senior and middle management (see the contractor's narratives in Case A).

In both cases, the architect and structural engineer either desired (Case A) or were already keen (Case B) to engage in informal communications with multiple tiers. Informal and across all tiers communication could, accordingly, facilitate both the implementation and alignment of BIM with SCM. After all, the until previously neglected relationship between suppliers and designers has been associated with enhanced trust, commitment, and knowledge transfer (Sariola & Martinsuo, 2016). The data converged in the existence of usually two main BIM-related roles: one of the project leader/engineer, who might or might not be familiar with the concept of BIM and one of the BIM modeller/engineer (Table 23). Again, in smaller firms these functions could be incorporated in one (Case A). The MEP engineers, whose design coordination with BIM has been studied in multiple instances, given the complexity of their tasks (Dossick & Neff, 2010; Wang & Leite, 2014), usually had three main intra-firm functions: tender manager, project engineer, and BIM modeller (Table 23). Additionally, the cases presented both disintegrated (Case A) and integrated (Case B) MEP-services firms, which could be evidence of a shift in increasing integration in AEC, by forming multi-disciplinary firms (Dulaimi et al., 2002). The integrated MEP services could subsequently transfer the inter-organisational coordination challenges intra-organisationally.

For the suppliers and sub-contractors, their involvement in the BIM-enabled SC partnership was mostly seen as an opportunity to engage earlier in design coordination (see the narratives of the suppliers), which in turn could contribute to greater integration in AEC (Dulaimi et al., 2002). The suppliers and sub-contractors had similar BIM-related intra-organisational divisions to the engineers and contractors respectively. BIM adoption from the SC partnership also induced transformations to their strategic IT investment, as some had adopted BIM intra-organisationally (Case A), whereas other had outsourced BIM use in BIM-drafting firms. The latter could in the future activate additional inter-organisational challenges, given that it would transfer the intra-firm communications outside the firm. Table 26 summarises the intra-organisational parameters that emerged from the data and contributed to the implementation of the BIM-enabled SC partnership. The categories in the left column are derived from the study of Dulaimi et al. (2002). Bresnen and Marshall (2000) have highlighted the relation between the intra-organisational cultural change and partnering. Also, Lambert et al. (1996) considered the compatibility and similarities of the top management philosophy and techniques as a good basis for strengthening the integration of the partnership.

TABLE 26 Emerging intra-organisational parameters that could influence the BIM-enabled SC partnership.

INTRA-FIRM PARAMETERS	DISINTEGRATED	INTEGRATED
Motivation for BIM/SCM adoption	External	Internal
Synergy among intra-firm hierarchy	Rigid hierarchy	Horizontal structure
BIM/SCM vision into firms' business plan	Occasionally applied vision	Incorporated vision
Intra-firm BIM-related functions	Three BIM-related functions	One all-around engineer
Services offered per firm	Specialised services	Integrated (e.g. MEP firms)
BIM implementation by the firm	Out-sourcing to external firm	In-house BIM implementation

§ 6.5.3 Strategies for further integration of BIM and SCM concepts

The study examined the combination of BIM and SCM by reflecting on their real-world inter-organisational interfaces regarding BIM adoption and implementation and proposed a conceptual model for facilitating future BIM-enabled SC partnerships. As planning is usually divided into strategic, tactical and operational levels (Ackoff, 1970; Mintzberg et al., 1996), these various levels also play a role in inter- and intra-organisational relations. Concerning strategical and tactical SCM, Ross (1998) acknowledged that "SCM is a continuously evolving management philosophy that seeks to unify the collective productive competencies and (...) business functions" across the SC partnership with the ultimate objective to deliver customer value. Additionally, some fine-tuning has to take place to align the firms not only strategically

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and operationally, but also inter- and intra-organisationally to BIM-enabled SC partnering. As opposed to Green et al. (2005) who claimed that the human agency and intra-organisational conflict are largely absent in SCM implementation, this study focused on the actors both inter- and intra-organisationally.

The following inter-organisational strategies, derived from the afore-described theoretical and empirical analyses could increase the understanding and potentially support future inter-organisational constellations that engage in BIM-enabled SC partnerships:

- Extension of the SC framework agreements to include explicit BIM scope;
- Balanced emphasis on both strategic (SC scope) and operational (BIM joint operations) planning;
- Proactivity in informal communications across multiple tiers, beyond contractual relations that could further ignite trust and increase commitment;
- Selection and alignment of firms with compatible BIM cultures.

The study also outlined implications for various AEC actors, such as the contractors, architects, engineers, and suppliers, at an intra-organisational level, to further support the previous inter-organisational strategies. Some strategies for an additional effort and support across all hierarchical levels within AEC firms to bridge the gap between digital technologies and professional roles and organisations could be:

- Increased internal communications across all hierarchical levels to fine-tune the planning of BIM-based projects and the operations in contractors' firms.
- Enhanced collaboration (and potentially integration) between architects and structural engineers, whose input is paramount for the initial BIM model;
- Evaluation of the trade-off between integrated MEP-engineering firms and isolated Mechanical, Electrical, and Plumbing engineering firms;
- Early involvement and frequent co-locations among engineers and suppliers;
- Strategic partnering from various disciplines to leverage from both market competitiveness and acquire BIM-related knowledge and skills;
- Conscious choice over integration or outsourcing of BIM-related services in various firms.

§ 6.5.4 Limitations and further research

The study focused on BIM-enabled SC partnerships only in the Netherlands. As the Dutch construction market is of *Corporatist type System* (Winch, 2002, p. 25), the AEC actors are likely to invest in operational, and strategic communications across all ties and potentially form alliances and partnerships. As the efforts to eliminate risks and uncertainties are according to Dorée (2004) '*engrained in Dutch culture*', the research findings could be relevant to other countries of the North-Western Europe. For cultural reasons and because the Dutch firms are characterised by a relatively 'flat' or horizontal organisational structure, the intra-organisational findings should be interpreted with caution.

Analysing the inter- and intra-organisational relations in BIM-enabled SC partnerships could contribute to further diffusing SCM philosophy and potentially enriching the insights into BIM implementation intra-organisationally. Further research could also address the impact that the client, owner, and facility managers have on inter-organisational relations, within or without a partnering scheme. Including the client could offer a more comprehensive image of the inter-organisational ramifications of BIM adoption and implementation.

§ 6.6 Conclusion

The appropriate inter-organisational structure to support BIM adoption and implementation is a heavily discussed topic across industry and academia. This study focused on the interplay between partnering and BIM and particularly on SC partnerships that extend across multiple tiers of the supply-side of AEC. After analysing two polar cases of BIM-enabled SC partnerships, several compatibilities and incompatibilities of BIM and SCM were identified. The analysis highlights the paradox of SC *Planning* considerations either as the result of *Joint Operations* (Case A, operational level) or pre-agreed SC *Scope* (Case B, strategic level). Another inter-organisational paradox is the consideration of *Communications* as the result of either pre-existing *Trust* (Case B, relational), or intensive *Joint Operations* (Case B, transactional). *The two cases highlighted that the trade-off between increased communications across multiple tiers and that the SC contractual relations are not mutually exclusive but greatly depend on pre-existing history and cultural alignment regarding adopting IT innovation, e.g. BIM* (answer to RQ#5, inter- part). To further strengthen the BIM-enabled SC partnerships, explicit scope, and BIM-related agreements are needed.

Whereas the unit of analysis of the study was the AEC firm, additional intra-organisational insights into the firms of engineers, contractors and suppliers were obtained. These inter-organisational insights relate to those firms adjusting their business models to BIM and SCM adoption, such as the vision and motivation for BIM and SCM adoption, inter-organisational synergy, and services offered. The BIM-enabled SC partnerships, guided by formal or informal rules, on operational and strategic levels, generated a dense but adaptable structure, which enabled the involved actors to pursue both intra- and inter-organisational goals. Simultaneously, it seems germane to diffuse the BIM knowledge at all intra-firm hierarchical levels, from top management to work floor. *The abundant discrepancy between the strategic and operational levels for the popularisation of BIM could be aligned by disseminating lessons from already contractually-bound multi-disciplinary teams with defined inter-organisational relations, i.e. SC partnerships. Accordingly, to further integrate BIM-enabled SC partnerships, conscious intra-organisational decisions about BIM and SCM motivation, BIM-related functions and BIM-related business models are preeminent* (answer to RQ#5, intra- part). Likewise, the adoption of digital technologies, such as BIM could play a role in rationalising the information flows among various types of AEC partnerships. The interplay between BIM with SCM practices could potentially contribute to the integration of the actors, and further digitisation and industrialisation in AEC.

7 Discussion: Synthesis and Validation

Chapter summary

Having completed the empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6) explorations of the emergent phenomenon of BIM-enabled SC partnering, the findings from each chapter are combined in a reflective and systematic manner to propose the research synthesis, or simply 'Synthesis' (RQ#6). The current evidence from scientific literature presents a shift of the BIM-related research to inter-organisational considerations. At the same time, the still ill-defined theory on SCM has had been largely associated with efforts for IT adoption across various aspects of the AEC, from the operations within the design offices to the construction site. Therefore, SCM philosophy could provide a basis for regulating the BIM-based collaboration and coordination processes and achieve integration. Simultaneously, from Chapter 6, some socio-technical considerations emerged regarding BIM-enabled SC partnering at strategic, tactical, and operational levels. This chapter systematically combines the research findings from the chapters 3 to 6 into the final research products to: (a) generate the theoretical synthesis, and (b) propose a set of strategies – or 'courses of action' – for BIM-enabled SC partnerships, under the conceptual P/P/A framework developed in Chapter 2.

This chapter apart from presenting the synthesis of all the research findings and discussions, it concludes the research by featuring three consecutive validation steps. Three different validation steps were pursued to cross-evaluate the research outcomes from external (to the research) feedback. Namely, the validation was sought at three levels adapted from Social Sciences' and Information Systems' research: (a) construct, i.e. constructs' operationalisation and methodology, (b) internal, i.e. from post-hoc analysis of the two deep polar case studies, and (c) external validity, i.e. with a panel of experts, sessions. Simultaneously, new material – not previously considered – was reviewed, such as new relevant scientific literature, e.g. latest publications and publications pertinent to the external feedback, recent National mandates, and other online resources. These validation steps are incorporated into the thesis to establish the research contribution, strengthen the research, and increase the usefulness and applicability of the 'Synthesis.'

§ 7.1 Introduction

§ 7.1.1 Integration as an antidote to complexity and fragmentation

As the AEC sector has been deemed predominately complex by numerous researchers (Azambuja & O'Brien, 2009; London, 2009; Vrijhoef & London, 2009), regarding its processes, products and actors, this study has focused on integration as an antidote to this complexity. Complexity usually relates not only to the agglomeration of numerous or infinite nodes and inter-relations in a system (Mitchell, 2009), but also to high unpredictability (Winch, 1998), and the lack or disruption of these inter-relations. The latter is related to the fragmentation of the industry into numerous SMEs and the subsequent low interdependency among them (Azambuja & O'Brien, 2009), which Nam and Tatum (1992) further defined as 'organisational disintegration'. Thus, three types of complexity were identified earlier in this treatise: processual (Gidado, 1996), product-related (Winch, 2002), and organisational (Nam & Tatum, 1992) complexity.

As those various complexities constitute a 'system of complexities,' accordingly, an equally systematic solution could counterbalance them, that is a systematic combination (Dubois & Gadde, 2002b, 2014) of integrations across the P/P/A dimensions (see section § 2.7). Integration in the construction industry has been seen as Supply Chain integration that focuses on industrialised production (Vrijhoef, 2011), procurement routes, such as IPD or DB, Integrated Design and Delivery Solutions (IDDS) (Owen et al., 2010; Owen et al., 2013), and integration of information systems (Dulaimi et al., 2002) across the various AEC lifecycle phases (Howard et al., 1989). Whereas various aspects of integration are applicable to AEC, this study focused only on the integrations that could induce a rationalisation and potentially minimisation of the three complexities above, that it of processes, products, and actors (P/P/A), through the lens of SCM and BIM. This conceptual model of AEC's complexity is like any other model – de facto – an abstraction of reality (Richmond, 2003). However, the study examined these complexities (processes, products, and actors) proportionally throughout the chapters, in an effort to understand their interpendencies. After all, in the context of SC research, Houlihan (1988) proposed that not only managing the interfaces of a system is required, but also integrating the multivariate components.

§ 7.1.2 Shaping BIM-based SC partnerships by aligning BIM with SCM

Drawing on from findings and strategies of the previous chapters (3 to 6) on the compatibilities and incompatibles of BIM and SCM, and comparing to the literature of Chapter 2, a set of comprehensive suggestions for future implementation of BIM-enabled SC partnerships could be extracted. Given that the aim of this study was not only to explore but also to synthesise, a set of network strategies will be (a) proposed, and subsequently (b) validated and revisited. The resulted set of network strategies will be presented in the form of a model or operational framework. The objectives of this chapter that will guide the 'Synthesis' are the following:

- Discussion about the nature and format of the Synthesis;
- Theoretical Synthesis and recommended strategies for BIM-enabled SCs;
- Validation of the research in three consecutive steps.

Based on the above objectives and the analysis and discussions in chapters 3 to 6, this chapter aims to reveal the conditions under which the topics under study, i.e. SCM practices, and BIM technology, could synergise to manage the inherent complexities and fragmentation of AEC industry in a long-term manner. Therefore, this chapter will focus on the *RQ#6: How could the BIM-enabled SC partnerships be shaped after the alignment of SCM philosophy with BIM technology?* The next sections will present the theoretical synthesis of the research, the proposed strategies, and afterwards, the discrete validation steps that will prepare the ground for the conclusion of the thesis.

§ 7.2 Nature and format of the Synthesis

§ 7.2.1 Use of theoretical and conceptual frameworks in research

In section § 2.1, the categorisation of complexities in AEC into processual, product-related, and organisational, suggested a preliminary form of a theoretical or conceptual framework. This categorisation emerged from literature review and the researcher's effort to present the literature in a semi-chronological manner, from the evolution of the concepts pertinent to SCM to the most contemporary concepts pertinent to BIM (see again Figure 5). Therefore, this conceptual framework was first presented in the background chapter to 'scaffold research' (Smyth, 2004). Undoubtedly, this framework might have included some initial bias. Additionally, during its development throughout the empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6) explorations of the emergent phenomenon of BIM-enabled SC partnering, slightly more emphasis was given on the 'actor' dimension. The conceptual framework of Chapter 2 will be revisited in this 'Synthesis' chapter modelled as an operational framework, aiming to identify the linkages among the theories of Chapter 2 and populate it with more levels and detailed components emerging from the findings and discussions of Chapters 3 to 6. The usefulness of the conceptual framework lies in creating a link between the background literature, and the research findings, but always by taking into consideration the underlying research methodology; regardless of which chapter influenced the findings most.

The afore-described conceptual framework of Chapter 2 largely 'scaffolded', strengthened and guided the research by (a) linking the background literature to the research questions, (b) informing the research design, (c) setting up points for discussions across Chapters 3 to 6 (Smyth, 2004), and (d) contributing to research trustworthiness of (Goetz & LeCompte, 1984). However, in relation to the latter, there are always points of further caution in research interpretation. Given that this treatise could be categorised in the intersection of Engineering, Management and Social Sciences, and the researcher is an engineer and not a social scientist, some implicit bias could be accounted for. Subsequently, the conceptual framework outlined in Chapter 2 has abundantly reflected the previous knowledge, previous professional experience, and life experiences of the researcher, who already had a 'tentative rudimentary conceptual framework' in mind (Miles & Huberman, 1994). Simultaneously, in Chapters 3 to 6, which were primarily based on case study methods, the conceptual framework might have consciously or unconsciously been informed by observations and enriched by relations bound with implicit personal sensitivities of the researcher, e.g. by noticing particular patterns and potentially ignoring others (Mason & Waywood, 1996). For this reason and particularly due to the use of case study methods, efforts to minimise the researcher's bias, such as long-term observation, peer examination, and disclosure of this bias per se, have been throughout deployed (Yazan, 2015). However, the initial conceptual framework remained open to new or unexpected occurrences in the findings (Smyth, 2004), with the ultimate goal to mature to a model or an operational framework that would link the various emergent theories. Evidence of this flexibility of the conceptual framework from Chapter 2 is the penetration of intra-organisational dimensions to the inter-organisational components of the study, although the initial Unit of Analysis (UoA) was the firm (Chapter 6).

Apart from cataloguing the various elements of the study, i.e. processual, product-related and organisational aspects of complexity, the conceptual framework of Chapter 2 attempted to move beyond the 'what' questions (see RQ#2 and RQ#3), which were inherently descriptive. Therefore, also 'how' questions, which are innately exploratory and explanatory, were deployed to understand the relations among processes, products, and actors through the lens of SCM and BIM. Additionally, 'why' questions were incorporated in the case study research design to provide insights into the motivations of the involved firms to adopt SCM and BIM, as well evaluate their commitment to adopting them, i.e. internal or external motivation (see Appendix C). Finally, the conceptual framework will be transformed into a model or an operational framework by enriching its components with the relationships that would answer the 'how' questions and particularly the question on 'Synthesis' (RQ#6).

§ 7.2.2 Use of operational frameworks or models in business

The conceptual framework would be appended a processual attribute (from the 'how to' questions that guided the research) to rationalise suggestive actions to implement future BIM-enabled SC partnerships. After all, the expected deliverables for this PhD were a "theoretical and operational framework" (see section § 1.1). In that sense, the conceptual framework would be transformed into an 'operational framework' or 'operational model' from a business perspective. A model or operational framework usually describes the strategies to achieve a goal, i.e. the sequence of steps to accomplish a particular objective. Apart from describing the properties that partake in the research, i.e. 'what' frameworks, it also shows the inter-relationship among these properties or components of the research. There are no clear components to be included in an operational framework. However, from business and practice, an operational framework often presents in a tangible manner how an organisation deploys its policies, standards, processes, procedures (tactics), tools, and training to achieve its objectives. However, in this study, the focus is the SC, which essentially is a constellation of numerous and various firms. Therefore, to define, document, and communicate the strategies – or 'courses of action' – to implement BIM-enabled SC partnerships, the majority of the components would emphasise on prescribing, guiding and governing their interactions. The objective of the proposed operational framework, i.e. the set of strategies for BIM-enabled SC partnerships, would be to provide a flexible identification of strategic resources and capabilities to create and manage BIM adoption and implementation in a contractually-bound partnership. It would be flexible so as to adapt to the scope of each SC partnerships, the changing contexts across projects and at the same time allow for evaluation of their performance. The research synthesis could provide an empirically derived operational framework as an instrument to inform and support the top management and the work floor of the various firms involved in the partnerships. The next section presents the generation process and the resulted 'Synthesis'.

§ 7.3 Synthesis of a model for BIM-enabled SC partnerships

§ 7.3.1 Dimensions of the Synthesis

The initial conceptual framework from Chapter 2, i.e. the Process/Product/ Actor (P/P/A) framework, could be further shaped and enriched from the findings of Chapters 3 to 6. Given that the findings have already been confronted to literature and filtered from the respective chapters, these would be compared, if appropriate, to additional or recent scientific literature, to obtain new insights. Only the findings from Chapters 3 to 6 that were confronted to scientific literature in the discussions sections of the respective chapters will participate in the theoretical synthesis and the proposed operational framework. Therefore, no circumstantial findings or isolated observations from the case participants will be included. The following sub-sections present the processual, product-related, and actor-related considerations that could play a role in proposing network strategies for BIM-enabled SC partnerships. In the following sub-sections, the content has been organised according to the empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6) explorations, and the P/P/A framework from Chapter 2. Figure 32 illustrates the process towards the theoretical synthesis and the current step, i.e. the summary of the discussed findings from Chapters 3 to 6.

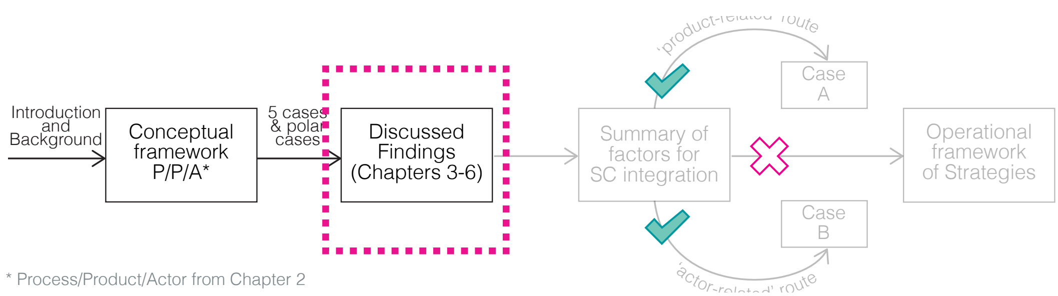

FIGURE 26 Collation of the discussed findings from Chapters 3 to 6 and their contribution to the research synthesis.

Whereas throughout Chapters 3 to 6, emerging, and unexpected observations and findings pertinent to various actors of the SC were discussed, e.g. the architect, contractor or suppliers, the theoretical synthesis and the resulted model of strategies will not focus individually on the various actors. The study held a multi-actor network perspective and to further instigate integration, no differentiation among the various actors will be pursued. Viewing the actors as an inseparable team is to align with the initial research decisions of not focusing on 'focal' firm, which has been followed in previous SCM theses, e.g. Vrijhoef's (2011, p. 236). After all, a potential differentiated generated theory per actor would additionally contribute to fragmentation and further hinder integration in AEC. The proposed strategies will be relevant to all engineers, contractors, and suppliers. Generating a holistic framework applicable to all actors will increase their joint understanding and insinuate the steps for achieving integration beyond organisational boundaries, across multiple tiers. Thus, the main dimensions of the operational framework would be processes, products, and actors.

Processual dimensions of integration from BIM-enabled SC partnering

The findings did not focus proportionally on all process-, product-, and actor-related aspects because these concepts did not emerge from the data collected and analysed across the various Chapters with the same frequency. First, an important observation that emerged from the empirical explorations of Chapter 3, was the discordance between the BIM implementation perceived at an inter-firm level, i.e. readiness, capacity and maturity (Succar & Kassem, 2015), as opposed to the collective capacity of the SC to implement BIM in the various processes. Second, the SC partnerships were aligning their processes to the specifications of Dutch BIM-related policies, such as the BIM Norm published by the Rijksgebouwendienst (2012) – now called Rijksvastgoedbedrijf –, which was , in turn, influenced by the publication of basic BIM requirements by its Norwegian equivalent, Statsbygg (2011). Third, three BIM-based collaboration patterns emerged from the empirical explorations (ad-hoc, linear, and distributed) that underlined the various BIM implementation processes from BIM-enabled SC partnerships, which suggest that although the medium might change the collaboration processes are largely driven by sequential and ad-hoc approaches, not taking the full potential of object-oriented modelling and BIM under consideration. Accordingly, the SCs would have to take full advantage of BIM advancements to support their collaboration and coordination.

The conceptual and pragmatic explorations focused more on the digital and physical collaboration and coordination of the projects undertaken by the BIM-enabled SC partnerships. Regarding the digital collaboration among the SC actors, from Chapter 4, a mismatch between the ingoing and outgoing inter-organisational interactions was observed. In the conceptual explorations of Chapter 4, also vague and continuous and obscure boundaries of the design and pre-construction phases were observed, potentially due to the time pressure that characterised most of the projects, or due to the intricacy of the BIM coordination process. This observation was extracted not only from the analysis of the project documentation but also by comparing to National standards for defining the boundaries of the construction phases. Berlo et al. (2015) reached similar conclusions across collaborative engineering processes in the Dutch AEC sector. Accordingly, various types of co-locations were observed in the two polar cases of the pragmatic explorations of Chapter 5. However, these co-locations were neither frequent at the initial stages of Design, nor time-wisely strategically placed. For example, in Case A, they took place after the construction had begun. The physical co-locations of the design and engineering teams resembled the attempts to optimise the design and construction process by 'concurrent engineering' (Lee, 2014; Alhava, Laine, & Kiviniemi, 2015), which aims to increase process integration in isolated design tasks, neglecting the typical and conventional division of phases. Another important emerging concept from the pragmatic explorations was the function of the BIM coordinator, as the collaboration with BIM is a distributed process, yet still in need of a formal role to coordinate the design process and the inter-organisational interactions.

These findings concur with Davies et al. (2015) that both technical skills and social competences would be necessary for the future BIM-related professionals.

The additional theoretical explorations of Chapter 6, delved deeper into the analysis of the two polar cases, driven from the various inconsistencies in the project planning and the overall time pressure that was reported in the polar cases. From this analysis, first, a gap between the strategic and operational planning was observed at usually the contractor's firms. The scope of the SC was malleable in order to meet a competitive advantage in the market, usually ignoring the individual commercial decisions and strategies at a firm level. Accordingly, the commercial decisions of the top managers were rarely in sync with the capacity of the engineering teams at an operational level. Whereas, 'top management support' has usually been associated with positive outcomes in the adoption of SCM and strategic partnering or alliances (Mentzer et al., 2001; Min & Mentzer, 2004; Jacobsson & Roth, 2014), only a few studies in BIM have underscored its importance. Throughout the cases, an additional synergy among tender managers, project leaders, and BIM engineers at an intra-organisational level was desired to align the inter-organisational processes (e.g. project initiation and project execution) to the intra-organisational. Subsequently, the intra- and inter-organisational processes could be supported by increased internal communications across all hierarchical levels to facilitate the BIM process inside their firm.

Product-related dimensions of integration from BIM-enabled SC partnering

From the empirical explorations of Chapter 3, various product-related aspects of integration surfaced from the data. First, some existing Dutch standards and policies for BIM specifications were taken under consideration, e.g. prescriptions for the 'BIM Protocol' or 'BIM Execution plan', which apart from the processual aspects mentioned above, define product-related specifications of the information exchange (2012). For example, these specifications attempt to create clear accountability of the design and production of the BIM models. However, from the SC partnerships both proprietary and open standard deliverables, i.e. IFC, were used. In the cases, where open standards were exchanged, these were usually checked using model checking tools, such as Solibri, which has largely penetrated the Dutch construction market (Berlo et al. 2015). However, there is a lot of ambiguity from the client's side on what the type of requirements that fall under the 'as-built' BIM category. This ambiguity usually induces challenges not only in the accountability of the design but also to the inter-organisational relations of the SC partnerships. Namely, the scope of the project, as to the LODs was a constant source of ambiguity among the design and engineering team. In retrospect, this should have been more clearly set in the BIM protocols or BIM execution plans. Some recent initiatives among thirteen prominent contractors in the Netherlands involve the standardisation of the requirements for the exchanged IFC files among the various AEC actors (Berlo & Papadonikolaki, 2016). This initiative is expected to influence several sub-contractors and suppliers, given that these contractors usually have long-term relations and partnerships with smaller enterprises in the market.

During the conceptual explorations in Chapter 4, many discussions were made on the promise of interoperability from using IFC during information exchange among the various actors. Whereas IFC faces some semantic challenges, it is the main open standard for the AEC (Amor, 2015). However, surprisingly, there is still recent research that claims that the lack of interoperability is still a challenge for BIM adoption (Ahn et al., 2015). Trying to debunk this myth, both the empirical and pragmatic explorations, have presented evidence that the inter-organisational complexities and not the interoperability with IFC are the most persistent challenges for AEC. Likewise, to counterbalance these inter-organisational complexities, the pragmatic explorations of Chapter 5 presented the physical, e.g. spaces or facilities with provision for IT, and digital, e.g. the CDE websites, infrastructures deployed to support not only the interoperability but also the interactions among the actors. At the same time, to complement the integration of the product-related aspects, the product-based collaboration was reinforced by proactive and complementary informal communications via ad-hoc means, such as emails with 2D drawings, and phone calls.

During the theoretical explorations of the BIM-enabled SC partnerships, in Chapter 6, various considerations that could assist the product-related integration in AEC emerged. A major consideration was the investment in digital technologies and BIM, which entails not only acquiring the software but also potential supporting infrastructure, like servers and physical or digital facilities. Therefore, a deliberate choice over the type of investment in BIM has to take place among the SC partnerships. For example, the data showed firms that were either training their in-house personnel in the use of BIM models or were out-sourcing the BIM services to external specialised firms. With respect to the latter, the coordination mechanisms when outsourcing BIM to an external firm becomes more complex, as there is an extra link added to the chain of the SC partners. Likewise, there are also projects where the BIM services have been completely out-sourced to a single BIM specialised firm, which could hinder the integration of the SC, as the coordination mechanisms become centralised (Aibinu & Papadonikolaki, 2016), rather than decentralised, as presented in the conceptual explorations in Chapter 4. The investment in BIM, according to Son et al. (2015a) is associated positively with top management support, at a firm level from a resource-based viewpoint. Nevertheless, the alignment of all involved SC partners with the type of investment in BIM has to be taken jointly or at least after recognising the various ramifications of the decisions to outsource BIM implementation to BIM-offering specialised firms.

Organisational dimensions of integration from BIM-enabled SC partnering

Several inter-organisational components of integration were discovered throughout the study. All Chapters 3 to 6 contributed equally to underpin these observations from the data to the theoretical contribution. The empirical explorations of Chapter 3, presented data about an alignment of the SC partnerships with the firm-related BIM readiness was observed, which has been previously discovered by Mahamadu et al. (2014). The SC partnerships tend to support their partner selection processes by choosing partners who are either already proficient or familiar with BIM. However, in instances where the partners' BIM competency was not advanced, some contractors support them by offering BIM training. The relations among the SC partners were usually governed by explicit formal SC framework agreements as previously defined in (Pryke, 2004). However, it was also observed that regardless the type of contract, i.e. year-contract, product-contract, long-term contract, the partners perceived their relations as SC partnerships. Thus, sharing previous experience, with or without BIM was a greatly supporting factor for achieving inter-organisational integration.

The conceptual and pragmatic explorations deployed some quantitative methods to investigate the factors to achieve inter-organisational integration. Initially, the data showed that there exists an imbalance as to the involvement of the internal, or strategic, and external partners of the SC (Chapter 4). This imbalance would outline implications to the collaboration and coordination, given that the position, power and influence of the actors in the chain are not proportional to their contractual position. From the pragmatic explorations, the early involvement of the various installation engineers and suppliers in the Design and Engineering phases was deemed possible under close SC partnering relations with long-term contractual arrangements and could contribute to increasing the understanding and enable joint decision-making among the various actors in the chain (Dossick & Neff, 2010; Wang & Leite, 2014). As a consequence of the early involvement, the various actors in the chains were encouraged to initiate and cultivate informal communication across multiple tiers, e.g. between architects and suppliers. The data from the pragmatic explorations of the two polar cases revealed two distinct approaches to SCM and SC partnering: a transactional and a relational approach, which gave more emphasis on the soft competences of the involved actors. The actor's soft competences have also been deemed equally important to the collaboration with BIM (Davies et al.2015; Y. Liu, van Nederveen, & Hertogh, 2016; Papadonikolaki & Oel, 2016). Regardless the long-term contracts in both polar cases, the commercial decisions were driven by different motives.

The previous observation suggested an additional level of consideration about SCM, which relates to the alignment of motives of the various firms to engage in BIM and SCM, i.e. whether the motivation was external, from the market, or internal, driven by the firm's need to change and innovate. Subsequently, regarding SCM, not only the top management support (Mentzer et al., 2001; Min & Mentzer, 2004) but also the depth into which the SCM culture penetrates the firm is paramount to their engagement. Sharing a common future vision for both BIM and SCM is necessary but not alone sufficient to diffuse the vision across the whole firm. Subsequently, a relevant strategy suggested from the data was the establishment of permanent contact person across the SC firms, so as to incite trust via increased collaboration and commitment, as. Mentzer et al. (2001) explain, and not from simply relying on the senior-level decisions and wishes. Likewise, this increased commitment could additionally entail inter-firm BIM peer-learning and training either at a project- or at an inter-organisational level, or during post-project evaluations. Among the surprising findings of the final theoretical explorations from Chapter 6, was the emergence of patterns and strategies from Dulaimi et al. (2002), according to which, partnering with firms with integrated business models, such as MEP or integrated Consulting and Engineering firms, could reduce the number of inter-organisational interfaces and increase integration in AEC.

§ 7.3.2 Levels of the Synthesis

The level of analysis of the study was the firm (or organisation). The theoretical synthesis of the BIM-enabled SC partnerships was made as to categories of processual, product-related, and (inter-) organisational dimensions. However, in Chapters 4 and 6, and particularly sections § 4.2 and § 6.5, additional intra-organisational insights into the firms engaged in BIM-enabled SC partnerships emerged, which proved to be crucial for the understanding and ramifications of the implementation of BIM from SC partnerships. Whereas the categorisation in processes, products, and actors emerged from the literature and the researcher's attempt to rationalise the various developments and concepts semi-chronologically, the inter-relations emerged from the various explorations undertaken: empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6). However, from the previous sub-section § 7.3.1, some similarities across strategies and operations were observed in the processual, product-related, and organisational dimensions of integration.

Therefore, to present the synthesis of the conceptual framework (Chapter 2) with the empirical (Chapter 3), conceptual (Chapter 4), pragmatic (Chapter 5), and theoretical (Chapter 6) explorations of this emergent phenomenon, the inter- and intra-organisational findings were combined. To illustrate the various levels of the framework/model, the well-known pyramid of Strategic, Tactical, and Operational (STO) decision-making in firms was used, as shown in Figure 27. Ansoff (1965, p. 8) distinguishes three types of decision-making processes inside a firm: (a) operational, (b) administrative (or tactical), and (c) strategic. The strategic decisions are primarily concerned with external rather than internal considerations of the firm, e.g. as to its competitive advantage, growth, finances, and purchasing strategy (Ansoff, 1965).

On the contrary, the operational decision-making pertains to daily decisions about efficiency and effectiveness; whereas the tactical decision-making ensures the right conditions to deploy strategies and support the operational decision-making (Ansoff, 1965). However, given that the phenomenon of BIM-enabled SC partnerships was studied in the Netherlands, where the organisations tend to be more horizontal, the tactical decision-making could occasionally overlap with the operational or strategic decision-making. Potentially, in other contexts, the administrative level of decision-making 'absorbs' the conflict between strategy and operations (Ansoff, 1965, p. 8). The theoretical synthesis then leads to a set of strategic, administrative, and operational steps for collaboration, coordination, and ultimately integration of the products, processes, and actors and the facilitation of the decision-making in the SC partnership.

FIGURE 27 The strategic, tactical and operational levels of decision making (adapted from Ansoff [1965]).

§ 7.3.3 Input for the Theoretical Synthesis

The theoretical synthesis based on the findings from Chapters 3 to 6, has been tabulated as to the processual, product-related, and actor-related dimensions and across the strategic, tactical, and operational levels that these pertain. Based on the discussed findings of the Chapters 3 to 6 and their recapitulation during the previous sub-section § 7.3.1, the following table contains the summary of the findings. This summary would lead to the theoretical synthesis and then to the proposed operational model of strategies to instigate integration in future BIM-enabled SC partnerships. Table 27 contains the factors of integration classified into processes, products, and actors, from Chapters 3 to 6. The columns contain the dimensions of process, product, and actors, from the conceptual P/P/A framework of Chapter 2. The rows organise these factors into hierarchical levels. Table 28 presents the key (neutralised) concepts of Table 27, i.e. the main topics of the factors without the suggestive actions.

TABLE 27 Classification of factors that could counterbalance the complexities in AEC and induce integration from the combination of SCM and BIM, as presented in Chapters 3, 4, 5 and 6 (in parentheses: sub-section and page number).

LEVEL	PROCESSUAL INTEGRATION – PROCESS	TECHNICAL INTEGRATION – PRODUCT	ORGANISATIONAL INTEGRATION & DISINTEGRATION – ACTORS
Strategic	– Alignment of the firms' BIM readiness levels with the SC's BIM implementation level (§ 3.5.1, p.86)*. – Adjustment of the SC planning about the SC's scope and commercial decisions (§ 6.5.1, p.165). – Intra-organisational synergy between tender managers, project leader and BIM engineer (§ 6.5.2, p.167). – Adherence of BIM implementation process to National policies (§ 3.5.2, p.87).	– Engagement in Open BIM Standards, e.g. IFC (§ 3.5.1, p.86). – Conscious choice over in-house BIM investment versus out-sourcing BIM services (§ 5.5.2, p.147, § 6.5.2, p.167). – Joint SC agreements on the BIM LOD (§ 3.5.2, p.87, § 5.5.1, p.145). – Top management support for BIM adoption (§ 5.5.2, p.147, § 6.5.1, p.165) – Joint SC agreements about the BIM protocols (§ 5.5.2, p.147). – Alignment of the BIM models with local BIM specifications (§ 3.5.2, p.87).	– Selection of BIM-savvy SC partners (§ 3.5.1, p.86, § 5.5.2, p.147). – Agreement on explicit formal SC framework agreements (§ 3.5.1, p.86, § 5.5.1, p.145, § 6.5.2, p.167). – Partnering with firms with integrated business models, MEP firms (§ 6.5.1, p.165). – Alignment across firms with compatible internal or external motivation for BIM adoption (§ 5.5.3, p.148, § 6.5.2, p.167). – Top management support for SCM adoption (§ 5.5.2, p.147, § 6.5.1, p.165). – Prioritisation between 'price' and 'collaboration' SC goals (§ 5.5.3, p.148).
Tactical	– Clear designation of the BIM coordinator's role (§ 3.5.1, p.86, § 5.5.2, p.147). – Frequent and time-wisely strategical co-locations (§ 3.5.2, p.87, § 4.6.3, p.117, § 5.5.3, p.148). – Elimination of the gap between strategic and operational planning at a firm level (§ 6.5.2, p.167).	– Alignment of project scope/clear scope with BIM's LOD (§ 3.5.2, p.87, § 5.5.2, p.147). – Clear accountability of the design/production (§ 3.5.2, p.87). – Use of model checking applications and tools (§ 3.5.1, p.86). – Prioritisation between the proprietary and open type of deliverables (e.g. IFC) (§ 3.5.1, p.86).	– Inter-firm BIM peer-learning and training (§ 5.5.3, p.148, § 6.5.1, p.165). – Establishment of permanent contact persons across the SC firms (§ 5.5.2, p.147). – Early involvement of the suppliers in the Design and Engineering phases (§ 5.5.3, p.148, § 6.5.2, p.167).
Operational	– Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns (§ 3.5.1, p.86). – Reciprocal ingoing and outgoing inter-organisational interactions (§ 4.6.3, p.117). – Adaptability to flexible/obscure phase boundaries (§ 4.6.3, p.117, § 5.5.2, p.147). – Increase of intra-firm communications (§ 6.5.1, p.165).	– Exchange of IFC for consistent information flows (§ 3.5.1, p.86, § 4.6.3, p.117). – Provision of physical (IT prepared space) and digital (CDE) infrastructure for information exchange (§ 3.5.2, p.87, § 5.5.2, p.147). – Encouragement of proactive and complementary informal communications via ad-hoc means (§ 3.5.1, p.86, § 5.5.2, p.147).	– Existence of shared past experience, with or without BIM (§ 3.5.2, p.87). – Shared future vision for both BIM and SCM (§ 6.5.1, p.165). – Encouragement of informal communication across multiple tiers (§ 5.5.2, p.147, § 6.5.1, p.165). – Balance between the involvement of internal and external SC actors (§ 4.6.3, p.117, § 5.5.2, p.147). – Incitement of trust via increased collaboration and commitment (§ 6.5.1, p.165).

* To trace the statements back to the respective discussions, the parenthesis links to the sub-section and page numbers.

TABLE 28 Key (neutralised) concepts emerged from the classification of factors that could counterbalance the complexities in AEC and induce integration from the combination of SCM and BIM.

LEVEL	PROCESSUAL INTEGRATION – PROCESS	TECHNICAL INTEGRATION – PRODUCT	ORGANISATIONAL INTEGRATION & DISINTEGRATION – ACTORS
Strategic	– SC's BIM implementation – SC planning – Intra-organisational synergy – National policies	– Open BIM Standards – BIM investment – SC agreements on BIM LOD – Top management BIM support – SC- derived BIM protocols – Local BIM specifications	– SC partners' BIM readiness – SC framework agreements – Integrated business models – Compatible BIM motivation – Top management SCM support – SC goals
Tactical	– BIM coordinator's role – Co-locations – Planning at a firm level	– Project scope to BIM's LOD – Design accountability – Model checking tools – Proprietary and open formats	– SC BIM peer-learning – Permanent contact persons – Early involvement of suppliers
Operational	– BIM collaboration patterns – Reciprocal SC interactions – Phase boundaries – Intra-firm communications	– Exchange of IFC – Physical and digital infrastructure for information exchange – Informal communications	– Past experience – Future vision – Communication across tiers – Involvement of internal and external SC actors – Trust and commitment

§ 7.3.4 Visualisation of the Synthesis

The findings and the tabulated factors above present some similarities to concepts and suggestions of previous SCM or BIM frameworks, either conceptual or operational. For example, apart from the top-down strategies and policy mandates that participate in the above table, several components from other SC-related frameworks, such as those of Lambert et al. (1996), Tan (2001), Lockamy and McCormack (2004), and Min and Mentzer (2004) have emerged. However, given the categorisation under strategic, tactical, and operational decision-making, several external and internal aspects of SC frameworks, such as the 'drivers' and 'facilitators' of Lambert et al. (1996) are incorporated in the organisational aspect of integration. Other similarities are found to the constructs of 'trust', 'contracts' and 'communication' (Lambert et al., 1996; Min & Mentzer, 2004). According to Kotzab et al. (2011), SC frameworks such as those of Lambert et al. (1996), Tan (2001), and Mentzer et al. (2001) have primarily emphasised on internal and external conditions for adopting SCM-related processes. Therefore, these SC frameworks are more of the "what" type of frameworks, which focus on listing components and conditions for SCM.

Regarding BIM, the above factors to achieve integration in AEC via the intersection of SCM and BIM, share some similarities with other BIM- or Construction IT-related frameworks. The framework of Owen's et al. (2013) focused the concepts of Lean Construction (LC) with BIM and IPD, for Integrated Design and Delivery Solutions (IDDS). According to Owen's et al. (2013) IDDS framework, to achieve the maximum potential of the AEC sector, AEC needs to transform its capabilities holistically based on the intersection of the three imperatives of (a) integrated processes, (b) interoperable Construction IT, and (c) collaborating people. However, given that the IPD procurement routes are not applicable to all contexts (Sebastian, 2011, Holzer, 2015), a long-term perspective such as the visions of SCM could potentially support further integration instead. Some parallels could also be drawn to Succar's et al. (2012) framework, who identify three areas for BIM-related knowledge: (a) technology, (b) process, and (c) policy, at a firm level. All these frameworks are represented as Venn diagrams, borrowed from Set Theory in Mathematics, as shown in Figure 28. In those, each enclosed scheme, i.e. circle, represents a key topic, and any intersection shows the potential interactions of topics. However, such Venn diagrams have mainly a descriptive role, e.g. for a 'what' type of framework.

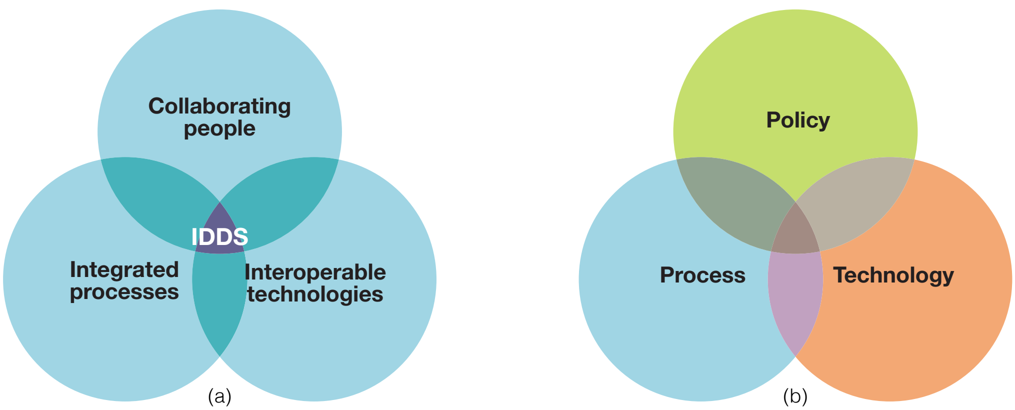

FIGURE 28 Other related frameworks on BIM, (a) IDDS framework adapted from Owen et al. (2013), and (b) BIM knowledge framework adapted from Succar et al. (2012).

According to Miles & Huberman (1994, p. 18), a conceptual framework is a written or visual organisation and representation of concepts that "*explains either graphically, or in narrative form, the main things (...) – the key factors, concepts or variables - and the presumed relationship among them*". The categorisation into product-, process-, and actor-related dimensions emerged from the semi-chronological interpretation of the literature on SCM and BIM by the researcher (see section § 2.7), the strategic, tactical, and operational levels of categorisation emerged from the raw data (from the case narratives) and the data interpretation. In Chapter 2, it was deduced that whereas the concept of SCM has emerged from processual considerations, it has acquired a pragmatic actor-related perspective concerning the multiple actors involved in the construction networks. Likewise, it was deduced that whereas the concept of BIM has emerged from product modelling and subsequently, product-related considerations could be attributed to it, given that BIM is a "set of instrumentalities"

(Miettinen & Paavola, 2014), it heavily affects the various involved actors who adopt and implement IT. Thus, whereas the two topics of SCM and BIM have both been associated with processes and products, respectively, an inter-organisational or multi-actors perspective was an essential aspect to be considered for their intersection (see "Remaining gaps and potential solution").

Whereas these three dimensions of process, product, and actors, were presented logically and chronically in that particular order in Chapter 2, the three concepts were re-arranged and associated differently for the synthesis of the generated theory from the empirical observations and analyses of the polar cases. To constitute the conceptual framework of Process/Product/Actor fully operational, a set of causal relationships derived from the empirical analyses was added. Although the constructs of products, processes, and actors could be easily represented as a Venn diagram, similarly to the frameworks in Figure 28, apart from the taxonomy of the factors of integration for BIM-enabled SC partnership, the relationships among the constructs of processes, products, and actors suggest two different routes to achieve integration. These two routes or approaches to achieve integration are derived from the two polar cases that participated in the deep polar cases' analysis of Chapters 5 and 6. These two routes form essentially the theoretical synthesis.

§ 7.3.5 Research Synthesis

Theoretical Synthesis

The next step, therefore, would be to generate theory about the two routes to integration, i.e. create the theoretical synthesis, on how the main research constructs, i.e. SCM and BIM, and their respective dimensions (P/P/A) could contribute to instigating greater integration in the construction industry. This theory stems mainly from the empirical observations of the previous chapters and particularly from Chapters 5 and 6, where the two in-depth polar cases were analysed and discussed. Whereas all Chapters 3 to 6 contributed to Table 27 and the tabulation of the discussed findings, those were subsequently compared only to the in-depth polar cases and the empirical findings of Chapters 5 and 6. The generation process of the theoretical synthesis, from the combination of the conceptual framework from Chapter 2 with the empirical findings from cases A and B is illustrated in Figure 29.

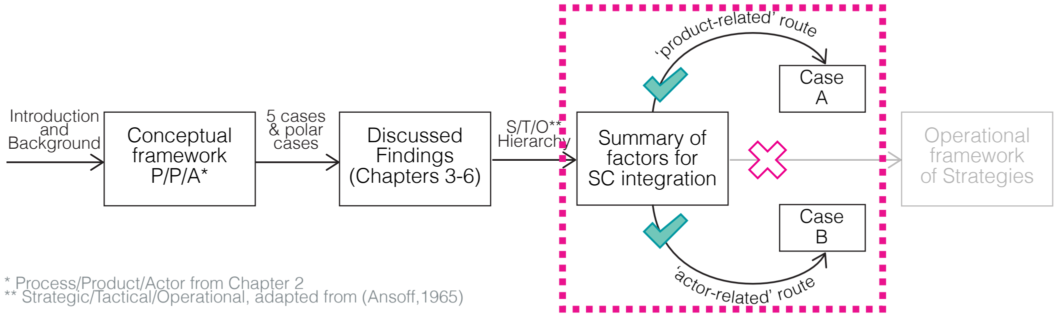

FIGURE 29 Process for the generation of the theoretical synthesis from comparing the findings of cases A and B.

The first route to achieve integration was displayed in Case A and mostly related to adherence to the product-related aspects of integration (Table 27, third column). The latter in turn could activate more coordinated processes that would finally eventually, generate greater commitment, and incite more trust among the SC actors. This route was revealed after comparing the factors for integration of Table 27 to the observed activities undertaken in case A, as presented and discussed in Chapters 5 and 6. The observed activities in the first route are shown in Table 29. First, the partners of case A, emphasised more on BIM-related strategies and policies, as well as they were deeply engaged in the use of Open Standards for consistent information exchanges. Simultaneously, they followed a quite sophisticated way to manage their physical and digital interactions (Table 29, second column). Second, the partners of case A were implementing slightly more sophisticated processes for their collaboration, e.g. alignment with strategic and national prescriptions (Table 29, third column). Third, the partners of case A apart from selecting BIM-savvy partners and implementing joint BIM training did not fully utilise the potential of SCM philosophy, so as to leverage their partnerships (Table 29, fourth column). From the above, Table 29 contains the observed activities in case A, re-arranged and prioritised into Product/Process/Actor, as opposed to the order Process/Product/Actor, previously established in the conceptual framework of Chapter 2 and presented in Table 27. This actor-related route to integration could be probably explained by the under-developed SCM philosophy in the contractor firm of case A, as opposed to their partners. At the same time, the SC partnership of case A was more focused on BIM, given that the contractor was part of a larger industrial consortium, actively engaged in the implementation of BIM and Open Standards in the Netherlands.

TABLE 29 Observed activities to induce integration in AEC deployed in Case A, presented in decreasing order of emphasis.

LEVEL	PRODUCT	PROCESS	ACTORS
Strategic	– Engagement in Open BIM Standards, e.g. IFC (Ch. 3). – Conscious choice over in-house BIM investment versus out-sourcing BIM services (Ch. 5, 6). – Top management support for BIM adoption (Ch. 3, 5, 6) – Alignment of the BIM models with local BIM specifications (Ch. 3).	– Alignment of the firms' BIM readiness levels with SC's BIM implementation level (Ch. 3). – Adherence to BIM implementation to National policies (Ch. 3, 6).	– Selection of BIM-savvy SC partners (Ch.3, 5).
Tactical	– Use of model checking applications and tools (Ch. 3). – Prioritisation between the proprietary and open type of deliverables (e.g. IFC) (Ch. 3).	– Clear designation of the BIM coordinator's role (Ch. 3, 5).	– Inter-firm BIM peer-learning and training (Ch. 5, 6).
Operational	– Provision of physical (IT prepared space) and digital (CDE) infrastructure for information exchange (Ch. 3, 4, 5).	– Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns (Ch. 3).	– Existence of shared past experience, with or without BIM (Ch. 3).

The second route to achieve integration was displayed from Case B (Chapters 5 and 6) and pertained to first utilising the actor-related aspects of integration (Table 27, fourth column). Accordingly, this decision supported the process coordination in such a way that could potentially, generate greater sophistication in the product-related aspects of integration and the utilisation of the full potential of BIM. This route was revealed after comparing the factors for integration in Table 27 to the observed activities undertaken in case B, as presented and discussed in Chapters 5 and 6. One, the partners of case B, emphasised more on their SC partnership and contracts and meaningfully engaged in horizontal, informal and across multiple tiers communications with their partners. At the same time, they valued their long-standing collaboration more than the achievement of a good price (Table 30, second column). Two, the partners of case B leveraged from their partnership during the establishment of frequent and pre-scheduled co-locations, which in turn supported them to manage the highly obscure project phasing (Table 30, third column). Three, in the partnership of case B whereas they engaged in the use of Open Standards, e.g. IFC, they did not fully utilise the potential of BIM, given that they did not use a sophisticated CDE environment but mostly ad-hoc communication means instead (Table 30, fourth column). Accordingly, Table 30 contains the activities undertaken in case B, re-arranged and prioritised in the order of Actor/Process/Product, as opposed to the order Process/Product/Actor (P/P/A), established initially in the conceptual framework of Chapter 2 (see again Table 27). This actor-related route to integration could be probably attributed to the imbalance between the SCM and BIM of the firms' top management. Given that the SC partnership of case B was more long-standing than the partnership of case A, the integration might resonate more with the emphasis on a multi-actor network, rather than simply the emphasis on the adoption and implementation of construction IT, i.e. BIM.

TABLE 30 Observed activities to induce integration in AEC deployed in Case B, presented in decreasing order of emphasis.

LEVEL	ACTORS	PROCESS	PRODUCT
Strategic	– Agreement on explicit formal SC framework agreements (Ch. 3, 5, 6). – Partnering with firms with integrated business models, MEP firms (Ch. 6). – Top management support for SCM adoption (Ch. 3, 5, 6). – Prioritisation between 'price' and 'collaboration' SC goals (Ch. 5, 6).	– Alignment of the firms' BIM readiness levels with SC's BIM implementation level (Ch. 3). – Intra-organisational synergy between tender managers, project leader and BIM engineer (Ch. 6).	– Engagement in Open BIM Standards, e.g. IFC (Ch. 3).
Tactical	– Establishment of permanent contact persons across the SC firms (Ch. 6). – Early involvement of the suppliers in the Design and Engineering phases (Ch. 5, 6).	– Frequent and time-wisely strategical co-locations (Ch. 3, 4, 5).	– Use of model checking applications and tools (Ch. 3).
Operational	– Existence of shared past experience, with or without BIM (Ch. 3). – Shared future vision for both BIM and SCM (Ch.6). – Encouragement of informal communication across multiple tiers (Ch. 5, 6). – Balance in the involvement of internal and external SC actors (Ch. 4, 5). – Incitement of trust via increased collaboration and commitment (Ch. 6).	– Adaptability to flexible/ obscure phase boundaries (Ch. 3, 4, 5, 6). – Increase of intra-firm communications (Ch. 6).	– Encouragement of proactive and complementary informal communications via ad-hoc means (Ch. 3, 5).

The first product of the research Synthesis, i.e. the theoretical synthesis of the two routes derived from Cases A and B is illustrated in Figure 30. The constructs of 'consistent information' and 'increased communication' pertain more to the construct of 'collaboration', which was the main focus of Chapter 3, whereas the construct of 'coordination' was abundant in Chapter 4, and of 'integration' in Chapters 5 and 6 respectively. Potentially further research would be needed to operationalise, weight, and validate the arrows, following the methodologies and tools described in Chapter 4.

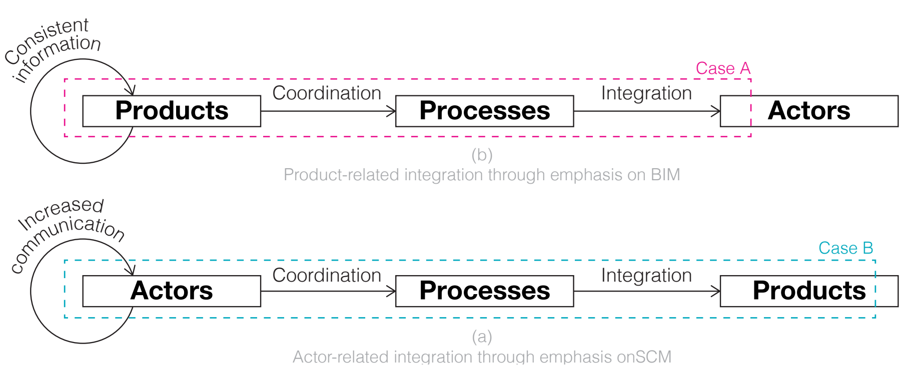

FIGURE 30 Two routes relating the processes, products and actors to achieve integration. The red dashed line on the top part evaluates the integration of Case A. The blue dashed line below indicates the integration of Case B.

Contrary to Fernie and Tennant's (2013) claims that the benefits "of holistically managed collaborative supply chains that compete are obvious" only to clients and not to any "other organisations" in the AEC sector, this study has focused on the latter group of firms. This study emphasised on the role of sub-contractors and the suppliers, as opposed to previous SC-related studies, by acknowledging that including the supplier network could provide opportunities for "joint learning" and further integration (Dubois & Gadde, 2000). The research argues that the existing SC partnerships would leverage from the mandatory adoption of BIM and that the networked organisations that already apply BIM would become more integrated, by adopting structures and processes of SCM. Whereas little analysis was made on the role of clients in these constellations of actors, some inferences could be drawn including this professional category as well. In general, however, the activities to counterbalance the complexities exemplified in cases A and B, do not focus on specific actors but instead target the whole multi-actor network. Thus, the following proposed 'courses of action' or strategies[9] are 'network strategies' as they approach the challenge of integrating the AEC SC through the alignment of SC partnering with BIM, from a joint perspective pertinent to all involved actors, without differentiating among them, e.g. as to contractors, architects, engineers. This would in turn increase the understanding and the accountability of the various disciplines in the SC.

Operational Framework

The second product of the research Synthesis, the proposed network strategies are presented in the form of an operational framework. Often the frameworks – either conceptual or operational –raise more questions than those that they attempt to solve. A relevant observation about the use of conceptual and operational frameworks is that "*people do not usually know what to do with the frameworks*"[10]. Therefore, two usability scenarios will be given for the two routes to integration presented before in Figure 30. On the basis of the above theoretical synthesis and taking under consideration the neglected aspects of integration from Table 27 throughout these two routes, i.e. the gap analysis, two sets of corrective strategies respectively could be deduced in the form of operational models presented in Table 31 and Table 32. The generation process of the operational framework from the combination of the conceptual framework from Chapter 2, the discussed findings in Chapters 3 to 6, and the theoretical Synthesis from cases A and B, are illustrated in Figure 31.

9 Here, the term 'strategy' is used as a proposed 'course of action' to integrate the BIM-enabled SC partnerships. Although the term 'strategy' usually pertains to a strategic level, we can also have strategies at a tactical and operational decision-making level, and thus it is an appropriate term.

10 Comment arisen during the Researcher's third Doctoral Progress Review on December 15th, 2015.

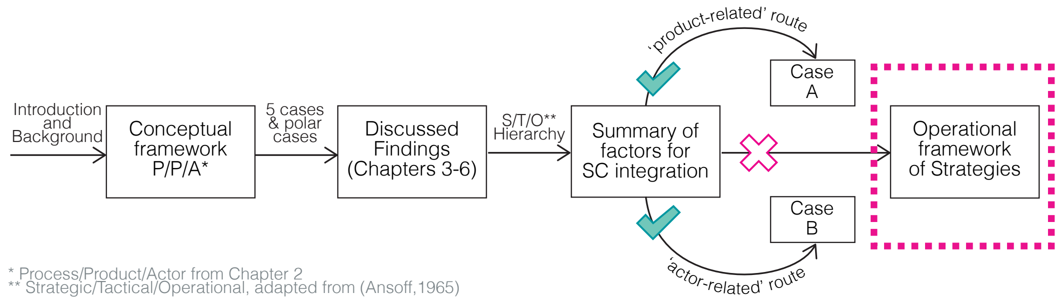

FIGURE 31 Process for the generation of the model or operational framework of proposed strategies.

These two sets of strategies essentially reflect the activities not undertaken in the cases A and B, given that the theoretical synthesis is derived from the empirical data. Note that, the two sets of strategies in Table 31 and Table 32 do not further differentiate as to the process-, product-, and actor- related dimensions. Given that integration is considered the opposite of differentiation, differentiating among the dimensions would eventually further impede the former. The proposed network strategies have derived from establishing further content relations across the hierarchical levels and integrating the concepts and activities omitted from cases A and B, where possible. However, these strategies continue focusing on the three hierarchical levels, i.e. strategic, tactical, and operational, given that these levels pertain to most intra-organisational environments and could facilitate the future adoption of these strategies from SC partnerships or other inter-organisational constellations.

TABLE 31 Proposed strategies to induce integration in AEC through the 'actor-related route'.

LEVEL	ACTORS -> PROCESS -> PRODUCT
Strategic	– Issuing explicit formal SC framework agreements combined with elements of BIM protocols; – Partnering with firms with integrated business models, e.g. MEP firms; – Partnering across firms with compatible internal or external motivation for BIM adoption and compatible SCM visions for prioritisation between price and collaboration; – Top management support for SCM adoption and inter-organisational synergy, e.g. among tender managers, project leader and BIM engineer; – Adjustment of the BIM scope (e.g. LOD) and planning to the SC's scope and commercial decisions.
Tactical	– Establishment of permanent contact persons across the SC partnership; – Early involvement of the suppliers in the Design and Engineering phases; – Pre-scheduling frequent and time-wisely strategical co-locations for BIM collaboration; – Elimination of the intra-organisational gaps between strategic and operational planning; – Joint agreements on the LODs and clear design accountability.
Operational	– Sharing a collective future vision for both BIM and SCM at a work floor level; – Encouragement of informal communication across multiple tiers; – Balance between the involvement of internal and external SC actors and reciprocal interactions; – SC partnership's flexibility and adaptability to obscure phase boundaries; – Increase of intra- and inter-firm communications to increase commitment and incite trust; – Digital information exchange via IFCs and proactive informal communications via ad-hoc means.

TABLE 32 Proposed strategies to induce integration in AEC through the 'product-related route'.

LEVEL	PRODUCT -> PROCESS -> ACTORS
Strategic	– Selection of BIM-savvy partners and conscious in-house BIM investment, instead of outsourcing; – Alignment of the firm-related BIM readiness with the SC partnership's BIM implementation level; – Partnering across firms with compatible motivation and top management support for BIM adoption; – Joint SC agreements about the BIM protocols and clear project/SC BIM scope; – Alignment of the BIM models with local BIM specifications and National BIM implementation policy.
Tactical	– Joint agreements on the BIM LODs and clear design accountability; – Clear designation of BIM coordinator and prioritisation between the proprietary or open deliverables; – Inter-firm BIM peer-learning and training; – Elimination of the gap between strategic and operational planning at SC and firm levels.
Operational	– Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns; – Reciprocal inter-organisational interactions; – Information exchange of IFCs and provision of stable physical (IT prepared space) and digital (CDE) infrastructure for BIM collaboration.

The above strategies for achieving integration via an 'actor-related' and a 'product-related' route have been derived from the empirical analysis of Chapters 3 to 6, and mostly from Chapters 5 and 6, where the two in-depth polar cases were analysed and discussed. These strategies could be selected by SC partnerships that desire to strengthen their SCM philosophy and implementation (Table 31) or their BIM strategy respectively (Table 32). Potentially, new partnerships that would desire to reach integration would have to combine elements from both tables depending on the maturity and level of development of their SCM and BIM strategies respectively. Finally, sets of firms that have no prior experience with neither SCM nor BIM could be benefitted by selecting the closest fit to their underlying managerial philosophy, i.e. actor-related or product-related, and accordingly their route to SC integration. As the management of change and innovation in organisations is impeded when it comes to people-related, organisational, or actor-related issues, potentially firms that carry no experience with SCM or BIM should potentially commence their route to integration by first focusing on the later, i.e. adoption and implementation of BIM. After all, throughout the narratives of the two polar cases, there is abundant evidence that these SC partnerships were not developed overnight, but were instead a complex network of conscious inter-organisational decisions and interactions that had been evolving for decades.

§ 7.4 Construct validation

§ 7.4.1 Consecutive Validation Strategies

After presenting the final research products of this PhD research, i.e. the 'synthesis', validation was sought and discussed. Creswell (1994) claimed that engaging in a combination of validation strategies, at least two, could deliver benefits to the researcher and add value to the study. The validation was divided into construct, internal, and external. The validation took place in three consecutive steps as illustrated in Figure 32. After each validation step, the PhD research was evaluated, as to construct, internal, and external validity. Subsequently, wherever a validation step conflicted with the research, different sets of research limitations were extracted, such as research and practical limitations (see Figure 32).

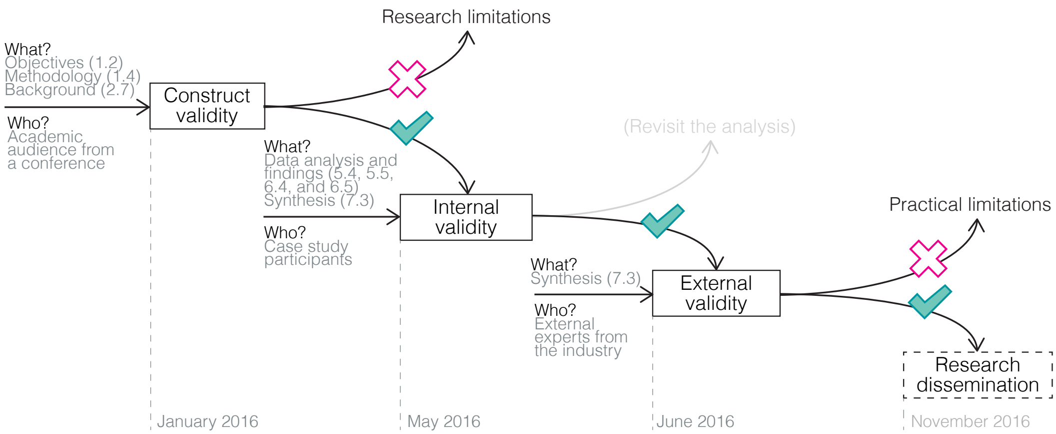

FIGURE 32 The three consecutive steps of the research validation process.

The first step of the validation would be a brief discussion of the epistemology and methodology. This discussion is necessary because it is customary that research is evaluated by linking back to the consistency in the line of reasoning and the chosen methodology. In total, three levels of validation were pursued, adapted from Social Sciences and Information Systems Research (Boudreau, Gefen, & Straub, 2001; Sarantakos, 2005). The validation included a (a) construct validity, or the extent to which the study explores what it claims to be measuring, i.e. constructs and methodology, (b) internal validity, i.e. from post-hoc analysis of the cases, i.e. whether the research 'instruments' were accurate (Boudreau et al., 2001), and (c) external validity, i.e. from an expert group (see Figure 32). These discussions will help the reader to understand, interpret, and contextualise the research products of this thesis.

§ 7.4.2 Reflection on methodology and epistemology

The 4th International Workshop on "When Social Science meets Lean and BIM" that took place at the University of Huddersfield, during the end of January 2016, was selected as a setting to spark a discussion on construct validity. This Workshop contained a very interesting mixture of academics; from the Social Sciences, Engineering and Management Science in the construction industry. The researcher presented the research aim, objectives, questions, and methodology of this doctoral research as well as some preliminary findings. Particular emphasis was given in the presentation of the constructs, i.e. SCM from an inter-organisational perspective, and BIM, from a socio-technical perspective. Apart from the investigation of the construct validity, another goal of this public interaction was to evaluate the extent to which this study was deemed relevant to other researchers in the area of Design and Construction Management. Only the feedback that aligned to the research topic, was contextualised to the reviewer's background, pertained to epistemology and methodology, and could potentially lead to generalisation, would be have been included in this thesis. The feedback from three prominent academics will be discussed next, namely:

- Reviewer A: Senior Researcher in Behavioural Sciences;
- Reviewer B: Professor in Construction Management and
- Reviewer C: Professor in Project Management and IT in construction.

Reviewer A recognised a potential value in studying the combination of BIM at the interface of SCM. However, for them, it remained "*open what is the inter-organisational context here*". This ambiguity is probably found on the theoretical grounds of SCM, which usually reflect connotations from operations management and the manufacturing sector, and not from a relational view of the firms engaged in SCM. For this reason, in this dissertation, the concept of SCM has been approached from a SC partnership perspective, i.e. a partnering undertaking has been considered a prerequisite for applying SCM philosophy. After all, London and Kenley (2001) had previously identified two main SC thinking schools, one focusing on the logistics, and the other on inter-organisational relationships. However, the ambiguity of the SCM philosophy has swayed severe criticisms about it, as it is usually associated with less competitive financial arrangements and unilateral control from a focal firm (Briscoe & Dainty, 2005; Green et al., 2005; Fernie & Tennant, 2013).

Regarding epistemology and methodology, Reviewer A noticed, that they "c*annot really comment on this part of the research*," because they are focused on qualitative research, and their "*aim is to 'operationalise' concepts through their emergence in* *practice*." Instead, in this dissertation, the main constructs of BIM and SCM have been already linked from the beginning of this doctoral assignment as a job description from MBE department at TU Delft (see section § 1.1). Reviewer A also advised caution with their comments because they "*represent a particular theoretical approach called cultural-historical activity theory that has its own principles regarding ontology, epistemology, and methodology*." Indeed, given that the researcher's background is found in the engineering practice and not in Social Sciences, some implicit bias and 'top-down' association of constructs could have penetrated into the research process.

Reviewer B, regarding the constructs used throughout the research, commented on the motivation and start of the research. For example, they posed questions such as:

"*Could you talk a bit more about the beginning of the work? Usually, you should start with a problem, e.g. a specific problem with BIM or with a specific SC of a company, or a particular segment of the SC that has problems. Or is there a gap of knowledge that you found through the literature? What was the initial problem that helped to define the scope of this research?*"

The research problem of this dissertation was initially defined as a continuation of the doctoral thesis of Vrijhoef (2011) with a particular focus on BIM. However, Vrijhoef's (2011) thesis focused only on specific and isolated parts of construction SCs, e.g. clients, contractors and designers. Therefore, the contribution of this thesis is not only found at looking to BIM as a potential to support the information flows of the SC, but also at focusing on actors, not isolated but instead bound in project-based SC partnerships.

Regarding methodology, Reviewer B, was interested in the main primary problem that triggered the research and established the research gap. They specifically looked for a problem driven from a particular company in the construction industry. However, given that this research on 'Supply Chain integration with BIM' defined the research problem in the industry – or Supply Chain – level (see section § 1.1); it was not triggered by a particular problem of a firm, but the MBE department was the 'problem-owner' instead. Reviewer B favours 'Design Science Research', which is similar to action research. Whereas the participatory action research could provide a solid basis for the rationalisation and specification of the research problem, according to Creswell (1994), it is bias-laden when dealing with qualitative data. The difference of this doctoral study is that it did not focus on one particular company, rather managed to recruit a variety of firms who engaged in both BIM and SCM to explore the various repercussions of the combination of BIM with SCM. The cases were recruited independently and did not participate in the definition of the research problem. Simultaneously, given that the researcher was not affiliated with any of these firms was impartial during the discussion of the research findings. No effort for impression management was made on behalf

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of the researcher, as opposed to the habit of "*polluting of the data*"[11] that takes place when the researcher is engaged in participatory action research and simultaneously affiliated with the firm under study. Moreover, given that this research was not firm-driven could be probably more relevant to a wider of organisations in the construction industry, either in the Netherlands or abroad.

Reviewer C focused more on how the constructs of the research were defined and less on the exact methodological decisions. First, they wondered to what extent the concept of SCM was used similarly to the Sir Egan's Report (1998), according to which "*the SC is re-invented in each project*". To this end, it was clarified that the concept of SCM was used with a long-term perspective, under which the projects of the cases followed, where 'interaction episodes' or 'snapshots' of the underlying long-term collaborations among the same firms. Second, they highlighted that:

"*One of the big issues we have with BIM projects is that with each project we have to sit down with all the partners and agree on a BIM execution plan and the workflow etc. It is very hard to optimise when you have to do this each time. So, I have a problem to see how BIM could be a way to put together SCM. You need to have repetitive projects to do that*".

The cases recruited for this doctoral research rarely involved repetitive projects. However, the composition of the SC partnership, e.g. contractor, engineers and some key suppliers, was repeated across projects. Most of the firms involved in the projects studied, moved with the same SC composition to following projects, afterwards. Therefore, the knowledge and experience about fine-tuning and agreeing on the BIM execution plans (or protocols) were transferred across projects. By issuing the SC framework agreements, the SC partners minimised the tendering time, and allowed more time to collaboration, by e.g. early involvement. At the same time, the risks were transferred at the initiation, rather than the design and execution of the projects. Third, Reviewer C highlighted that the SCM philosophy entails both information and material flows and that regarding the former this study is well attuned. However, it lacks the material-related focus. This doctoral research focused consciously on only the information flows, by considering information and material as the two sides of the same coin and by accepting the object-oriented modelling, e.g. BIM, as a structured way to represent the physical information about an artefact in digital form. After all, through BIM, information about the material delivery and quantities could be extracted.

As a 'take-home' message from the discussions in this workshop, two main topics should be further highlighted and restated: (a) the inherent limitations of the study, due to the researcher's background, and (b) the potential for generalisation from

11 Comment from the audience during the discussions that took place in the 4th International Workshop.

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the chosen approach. Undoubtedly, this thesis is at the intersection of engineering and social sciences (management) and of course might entail limitations, such as implicit bias, on behalf of the researcher, who is an engineer and not a social scientist. Accepting this background might contribute to understanding how the researcher arrived at the findings and conclusions and to what extent they could be generalisable. Whereas the research was explorative throughout the various studies, it is not inconclusive. As Bengtsson and Hertting (2014) point out, the potential generalisation from the case study research "is based neither on determinism nor probability, but on expectations about similar patterns of thinly rational action and interaction in similar contexts". Subsequently, the observations and findings emerged from the descriptive case analysis in Chapter 3, or from the deep analysis of the polar cases in Chapters 5 and 6 could lay the ground for repeatable methodologies and inferences in similar or at least comparable contexts.

§ 7.5 Internal validation

§ 7.5.1 Objectives and structure of the Workshops on Internal validity

After discussing the methodology during the 'construct validity' session, another validation step was used to discuss the research products. Both the *Analysis* and the *Synthesis* parts of the dissertation were confronted not only with the scientific literature but also with the experiences and ideas of practitioners from the industry. Subsequently, the next discussions about the research took place with two distinct goals: (a) to validate the analysis (sections § 5.4, § 5.5, § 6.4, and § 6.5) and synthesis (section § 7.3, Table 27 and Figure 30) internally, through post-hoc case analysis with the case participants, and (b) to validate the synthesis (section § 7.3, Table 27, Figure 30, Table 31, and Table 32) externally, through interaction with a panel of experts. The internal validity refers to the validation of the research findings within the setting of the study. Therefore, to investigate the internal validity, the results of the analysis and the Synthesis were confronted with the participants of the two polar cases, A and B. The goal was to evaluate the extent to which the researcher's findings were traced back to the actions and interactions of the real-world projects, investigate whether the analysis was accurate, and potentially gain new insights into the studied projects.

§ 7.5.2 Data collection and analysis method

Regarding the internal validity, two workshops with the participants of cases A and B respectively took place. The goal of these workshops was twofold; first to validate the analysis and the research findings, and second to reflect on the Synthesis as to what extent it could be applicable elsewhere. The feedback from the participants of the polar cases was essential for not only validating the analysis and interpretation of the data but also providing insights into the changing approaches of the participating firms.

Given that the study of the two polar cases lasted about one year and a half, and the projects were equally challenging, the project teams had to adjust quickly to emerging challenges that were not traceable from the researcher. These internal validation sessions attempted to capture post-hoc these adjustments as well. The internal validity sessions were similar to the research functions that Sarantakos (2005, p. 86) calls communicative validity: "the involvement of the participants – by checking accuracy of data, evaluation of project process and change of goals, by employing expert external audits and by using triangulation – in order to achieve multiple perspectives and to confirm authenticity". The 'Internal Validity' workshops were employed to examine the credibility, trustworthiness, and objectivity of the conducted research (Sarantakos, 2005, p. 86). The case participants of the two polar cases were solicited to assess the credibility of the findings and interpretations (Miles & Huberman, 1994), given that the case data derived from the interviews that they had previously openly shared with the researcher.

The input for the internal validation workshops was a presentation of a set of slides based on research products completed until the time of that the validation sessions took place. I nparticular, the material that was validated was primarily based on chapters 5 and 6 and in particular the data analysis (sections § 5.4, § 6.4), research findings (sections § 5.5, § 6.5), and on Chapter 7 as to the synthesis (section § 7.3, Table 27 and Figure 30). Table 33 describes the slides that contained material previously presented in this thesis: The first column to the left contains the distinctive parts of the presentation, e.g. introduction, background, and conclusion. The second column contains the number, title, and content of each slide presented. The third column to the left points out to the respective sections of this thesis, that the input for the validation session came from.

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TABLE 33 Organisation and content of the presentation slides for the input of the 'internal validation' workshop.

PURPOSE	SLIDE NUMBER AND CONTENT	SECTION IN THE THESIS
Introduction	1. Complexities in the construction industry; 2. Research questions;	§ 1.1 and § 1.2 § 1.3
Background	3. Overview of the followed case studies in the Netherlands; 4. Observed patterns of BIM-based collaboration; 5. Findings from the five cases; 6. Rationale for focusing on the two polar cases;	§ 3.3, Figure 10 § 3.4, Table 11 § 3.4, Table 13 –
Analysis	7. Basic characteristics of the two polar cases 8. Contractual and digital information flow networks of the two cases 9. Organisation and intensity of information exchanges per actor 10. Content of information exchanges per actor 11. Analysis of the narratives per actor emphasising on informal relations 12. Analysis of the narratives focusing on components of SC partnerships 13. Analysis of the narratives focusing on components of SC partnerships per actor 14. Intra-organisational aspects that affect BIM-enabled SC partnering	§ 5.3, Table 18 § 5.4, Figure 23 § 5.4, Figure 24 § 5.4, Figure 25 § 5.4, Table 21 § 6.4, Table 24 § 6.4, Table 25 § 6.5, Table 26
Synthesis	15. Synthesis of the factors for integrating BIM-enabled SC partnerships; 16. Two routes – 'actor-related' and 'product-related' – for achieving integration; 17. Proposed strategies to induce integration through the 'actor-related route'; 18. Proposed strategies to induce integration through the 'product-related route';	§ 7.3, Table 27 § 7.3, Figure 30 § 7.3, Table 31 § 7.3, Table 32
Closing	19. Summary and main points for discussion	–

The case participants were encouraged to reflect on the relation between the background and development of the project and the project outcomes. Both workshops with case A and B had the same structure and administration. The workshops lasted one and half hours and had the following structure:

- Introduction and update on the status of the research and distribution of hand-outs with the slides for personal notes (5 minutes);
- Presentation of the research analysis and synthesis (20 minutes);
- Open discussion and reflection on the research analysis by revisiting the presentation slides (30 minutes);
- Open discussion and reflection on the synthesis by keeping notes on the hand-outs with the proposed strategies of the operational framework (30 minutes);
- Closing of the session and recapitulation of the main discussion points (5 minutes).

However, because of the inherent differences between the two polar cases, as described and analysed in Chapters 5 and 6, the two Workshops in Internal Validity had different audience composition, which will be explained accordingly in the next sub-sections. Figure 33 illustrates the typical structure of the two main phases on the Internal Validity workshops: (a) presentation and (b) discussion.

FIGURE 33 Typical session of the internal validity workshop from Case B: (left) presentation and (right) discussion.

§ 7.5.3 Workshop with the participants of Case A

The Workshop in 'Internal Validity' for Case A took place on May 10th, 2016. Given that the findings from the analyses Chapters 5 and 6, provided evidence of a lack of collaborative culture throughout the SC of the project of case A, not all SC partners were invited to the workshop. The researcher decided that the level of collaboration and integration was not sufficient to incite a trusting and safe atmosphere, but the SC was price-driven instead. Accordingly, the Internal Validity workshop took place at the contractor's firm, with the goal to attract as many hierarchical levels as possible. Finally, three different project-based and firm-based functions, who had previously participated in the study, also participated in the workshop:

- BIM (with SC vision) Manager (firm-based);
- BIM Coordinator (project-based) and
- Design Coordinator.

The discussions during the workshop with the participants of case A were at two main levels; reflecting on the analysis of their project and also discussing the applicability of the proposed strategies elsewhere, either within their project portfolio, their partnerships or the Dutch industry in general. Overall, with regard to Table 33, slides 11 and 16, they stated: "*We recognise the patterns of the project in the analysis*" (BIM Manager) and "*I recognise the analysis and how you captured the beginning and the end of our project*" (Design Coordinator). However, they seized the opportunity to reflect more on their project on both SC-related and BIM-related aspects, about the following themes: (a) SCM strategy, (b) the interface between SCM and BIM, (c) the intra-organisational and tactical decisions about BIM, and (d) about the operational aspects of BIM-enabled SCs. Regarding the SCM philosophy, first, they acknowledged that some partners such as the structural engineer was feeling close to the contractor's firm without having yearly contracts (Table 33, slide 8), but only contracts for specific building products, probably because "*most partners work a lot with us*" (Design

Coordinator). Therefore, any long-term contract could instigate a SCM-culture (Table 33, slide 8). Second, they recognised that the greatest limitation of the project was the fact that "*with this project, we had a design from another architect at the beginning (...) If it was his own design, he would have been more responsible*" (Design Coordinator). Third, the partners acknowledged that "*we have to start with our partners earlier in the project*" (Design Coordinator) (Table 33, slides 11 and 15).

Regarding the interface between SCM and BIM, and slide 4 (Table 33), they identified the tensions when the various SC partners have varying motivations for adopting BIM, i.e. internal versus external motivation: "we *think it is important to select partners that recognise the value of BIM themselves*" (BIM Manager) and "*we know that BIM is the future and that all the partners have to adapt*" (Design Coordinator). They also acknowledged that during the one and a half years that the project progressed, some of their SC partners adjusted their business models to include BIM: "*some suppliers have changed their whole business plan to include BIM in all projects*" (Design Coordinator), and "*at the beginning of the project the steel suppliers were negative to using BIM but now they are doing so well, and they have almost all the projects in BIM*" (BIM Manager) (Table 33, slides 8 and 14). They concurred with the suggested activities (Table 33, slide 15) about BIM and SCM in the sense that "*you can do SCM without BIM, but the SC partnership will have more benefit when you do BIM*" and "*with different SC partners, the learning process takes longer than with the same SC partners*" (BIM Manager). They admitted that their firm's strategy is to increase their commitment to SCM, as "*we think that we can only survive if we have a good SC, for each project. We will have different SC partners for different types of project*" (BIM Manager).

The intra-firm hierarchy was a barrier for diffusing BIM knowledge. For example, regarding the varying functions: "t*he electrical engineers and installators had one person working at the beginning of the project and another at the end, but the experience of their BIM engineer expertise, who had 13 projects with BIM, was not diffused upwards in their firms*" (Design Coordinator), whereas "*from the ventilation engineering firm, people with all the hierarchical levels were at the BIM meetings, even though they did not have to BIM*" (Design Coordinator). This contributed to the sharing of BIM knowledge across the partnerships: "*our partners are very positive in the way we work with BIM because they see the experience of case A as a learning experience*" (BIM Manager) and "*it helps in the SC that we both learn together and grow together*" (BIM Manager). The sharing of BIM knowledge also took place outside the project: "*when we start the project we invite them, and we train them, but we also do sessions not project-oriented, for workshops*" (BIM Manager) "*If you need any help about BIM you can always call, don't be ashamed, always ask*" (Design Coordinator) (Table 33, slide 11). However, they highlighted that as a firm, they "*only facilitate Open BIM standards*" and "*the last two years it goes better and better with Open BIM, we had a lot of problems in the beginning*" (BIM Manager). Whereas they invest time in training their partners, "*we invest in joint BIM learning, but we only facilitate Open BIM*" (BIM Manager) (Table

33, slides 13 and 15). As they have been updating their BIM-related strategy, they have admitted: "*we have implemented the 'BIM-Basis requirements'*[12] *in our new projects. When we now close a deal with one clause about the requirement that they have to accept our BIM protocol and have a responsible person who knows BIM in their firm*" (BIM Manager).

Concerning the proposed strategies (Table 33, slides 17 and 18), they stated that the strategies could apply to all projects of the Dutch AEC market. However, they highlighted that possibly the suggestion about partnering with firms with integrated business models: "*this is more for the large and the complex projects (...) in small projects we do not need the same amount of coordination*" (BIM Coordinator). Moreover, they added that regarding the proposition about informal and horizontal communication across multiple tiers, their "*partners told us that they prefer to find pairs in similar disciplines and work together (...), coordinate with each other and then come to us with their decision. So we only have to facilitate these pairs*" (BIM Coordinator) and "*we trust them to find the best solution with each other" (...) and if we do more projects they know how we think*" (BIM Manager) (Table 33, slide 13). This is why recently they "*have started on some projects with 'concurrent engineering'*" (BIM Manager). Subsequently, they also supported the proposition for permanent contact persons across the firms: "*we have companies that switch the positions of the people inside all the time. But we have selected because the persons that worked over there, so we need permanent people inside those firms (...) to integrate the processes of design and engineering*" (BIM Manager) (Table 33, slide 13).

§ 7.5.4 Workshop with the participants of Case B

The Workshop on 'Internal Validity' for Case B took place on May 13th, 2016. Given that the findings from the analyses in Chapters 5 and 6, provided evidence of a highly collaborative culture throughout the SC of the project of case B, all SC partners were invited to the workshop. The Internal Validity workshop took place at a 'Pull-planning' room of the contractor's firm, where the pull-planning sessions and the BIM coordination sessions also took place during the project. The following SC actors and inter-organisational functions participated in the workshop:

- Site Engineer from the contractor;
- BIM Coordinator from the contractor;
- Project Leader from the architect;

12 For a review of this initiative, see the paper of Berlo and Papadonikolaki (2016).

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- BIM Engineer from the architect;
- Project Leader from the structural engineer;
- Project Leader from the sub-contractor;
- Tender Manager from the MEP firm and
- BIM Engineer from the MEP firm.

The workshop with the participants of case B included discussions on the interpretation of the project and the SC partnership. Surprisingly the discussions were not around BIM investment, training, and coordination, as in case A, but more about the role of the client and the formal agreements, from SCM or BIM perspectives. The participants unanimously agreed that the analysis of Table 33, slides 8 and 11, accurately portrayed their project. However, they emphasised on the role of the client in the project and devoted a large part of their reflection to evaluate how different scenarios about the client's involvement would have impacted the project outcomes. They compared the project studied in case B with the next professional undertaking of their SC partnership and decided that "*it is important to engage the client in the projects, as we are doing in our current project*" (Project Leader-Sub-contractor). Whereas in case B, "*the client did not want to come to the session to discuss, which was then a problem*" (BIM Engineer-Architect), because "*the client did not know what changes can be implemented it terms of requirements and cost. It is a mindset change*" (Project Leader-Architect). Upon the researcher's question whether the challenges above would be resolved if the clients were parts of the SC partnership, the partners agreed that:

"it is better to have the client as part of the SC partnership because it is better to have the tensions with them at the beginning of the project, rather than at the end. (…) This will force them to be more responsible in what they want. They cannot change it later on if they are committed earlier on" (Project Leader-Sub-contractor).

However, this would happen under conditions, because "*of course it depends on what type of client it is, public, corporation, owner, or developer*" (Project Leader-Architect). Another strategy to counterbalance these challenges at the demand side of the SC would be "*to communicate more the discussions with the client within the SC partnership*" (Project Leader-Structural engineer) (Table 33, slide 11).

In general, BIM was deemed by the case participants as necessary for increasing the collaboration and integrating the SC partners (Table 33, slide 4). Their rationale was that "*BIM gives better projects, because then you know each other and what to ask from your partners to think different and it helps to build trust in the long run*" (Project Leader-Architect). The Project Leader from the sub-contractor's firm underlined that this is applicable "*to all projects*" (Table 33, slides 17 and 18). However, all of them resonated with the previous and analyses throughout the research about the need to make clear and explicit agreements among the partnerships about the design accountability with BIM: "*the challenge is with BIM and SCM to know how to divide and* *exchange the drawings and the workload*" (Site Engineer-Contractor) (Table 33, slides 17 and 18). For this reason, they highlighted that they need to make a priori "*concrete agreements on who does what in the BIM process, (...) with SCM it is easier because we know each other, and we know what the other wants and expects us to do*" (Project Leader-Structural engineer). From the above their discussions linked to the suggested strategy for establishing permanent contact persons across the various firms. Having permanent contact persons per firm is a practice that some firms were already engaged on: "*we have specific people for specific partners or SC partnerships; it is easy this way, for this SC partnership, we have him*" [pointing to his colleague] (Tender Manager-MEP firm). On the contrary, in firms where this is not already a culture, "*we have to share better the (BIM) knowledge inside our company because it is a big company and it can get lost*" (Site Engineer-Contractor). The BIM Engineer of the Architect's firm highlighted that permanent contact persons would be useful "*in larger and more complex projects (...), because the risks of coordination are higher there*".

They concurred that the existence of their long-term relations and some SC contracts improved the integration among the partners. Whereas "*the risk is bigger at the beginning of the project during the contract agreement, regarding how much information you release (...) the more the contracts, the more the projects, the more is the trust*" (Project Leader-Sub-contractor) (Table 33, slides 12 and 13). The SC partners also reflected a lot on their habit of early supplier involvement and how they could be earlier engaged to the assignment; "*but we should not start if the ground-floor plan is not finished*" (Project Leader-Sub-contractor). It was for the afore-mentioned benefits of increased collaboration and trust that the partners admitted that, "*every firm is actively searching for new partners and SC relations either in large or small projects*" (Tender Manager-MEP firm). However, regarding the combination of BIM and SCM, that was deemed "*more difficult at the start of the projects with BIM and SC partnership, but then it becomes easier than in traditional projects*" (Site Engineer-Contractor). Therefore, they advised that "*having SC contracts can standardise the BIM use in projects and the collaboration, and they become more and more efficient from repetition*" (Site Engineer-Contractor).

Following on the previous discussions about the intersection of SCM and BIM, the partners concurred with the suggested strategy to combine the SC partnering contracts with some elements of the BIM protocols (Table 33, slides 17 and 18). More importantly, aligning with the National mandates and defining the project phases would be essential for counterbalancing the ambiguity of the processes: "*as the phases are defined by the financial agreements, and in practice by the LOD levels, these can be included in contracts, but they are unique per projects. We need as much information as possible at the beginning*" (Project Leader-Structural engineer). As in case A, they also admitted that the combination of contractual means and BIM protocols steadily becomes a common practice in the industry. For example, they stated: "*it is more and more often that we see the BIM protocol being a part of the contract, about who does* *what when*" (Project Leader-Structural engineer) and "*also to define the use of the CDE, the BIM libraries and many BIM details inside*" (BIM Engineer-MEP firm). The partners of the SC of case B have also started to follow the 'bottom-up' initiatives in the Dutch AEC market for regulating the exchange of building information with BIM, as did the contractor of case A.

§ 7.5.5 Reflection from the two Workshops on Internal validity

Before reflecting on the outcomes of the 'internal validation' session, a brief reflection on the methods of this session will take place. Overall, it can be stated that the composition of the participants in the two sessions was appropriate. For example, the participants were from both the managerial and engineering sides, and this reduced any selection bias. Comparing the discussions from the two sessions, the participants of case A reflected more on the project and the data analysis, whereas the participants of case B reflected more on the synthesis and the proposed strategies. This could be explained by the fact that the participants from the internal validation session of case B were from multiple firms, whereas of case A, only from one firm. A positively surprising fact was that, whereas the analysis was not always favourable to the case A, the feedback from the case participants validated the (negative) findings and also reflected on how to improve the suggested strategies for integration in AEC through BIM-enabled SC partnering. Finally, in both cases, it was concluded that the actors have already taken further actions to improve their processes and workflows, and this not only shows the appropriateness of the workshop participants but also highlights that essentially BIM is a highly dynamic field of practice, which constantly undergoes transition.

The discussions that took place during 'internal validity' workshops contributed to the validation of some proposed strategies from Table 31 and Table 32. Moreover, from the 'internal validity' workshops, some strategies were further refined and revisited and could be subsequently further tested for validation in the workshop of 'external validity'. The discussed strategies as well as new concepts that emerged from the internal validation workshops and could incite SC integration were:

- Partnering with any type of SC contract or framework agreement, regardless the price, quantity, and longevity details could also contribute to building trust among the SC partnership and supporting successful BIM implementation.
- In case A, the contractor firm recently started with enriching their tendering contracts with elements of BIM protocols and agreements adopted from the National BIM policies, and in particular, the agreements described from Berlo and Papadonikolaki (2016). Potentially such BIM-related requirements would also be incorporated in SC framework agreements.

- Establishing permanent contact persons across the firms was a practice that took place in some firms, from both cases. This could contribute to clearer design accountability, support BIM implementation, and potentially advance the dissemination of knowledge at both intra- and inter-organisational levels.
- In both cases, the SC partnership did not engage in joint BIM investment, and the partnerships did not prescribe which BIM software type to use. For this reason, they exchanged IFCs with the suppliers, who were using different BIM applications than the engineers. Except case A, where the architect had to acquire a different BIM software, to match the software used by the other engineers. The BIM-related investment in IT digital infrastructure, such as CDE was made from the contractors. However, all SC actors invested time in peer-training from the most advanced towards the less savvy SC actors. Thus, there are many aspects of BIM investment to facilitate SC integration.
- The concept of 'concurrent engineering' (Evbuomwan & Anumba, 1998), which is a common practice in SC partnering (Deshpande, 2012), emerged from the discussions with case A. Concurrent engineering is a popular activity that takes place in conjunction with BIM (Lee, 2014), in designated locations called Intensive Big Room (IBR) (Alhava et al., 2015). During the same discussion, the practice of 'pairing' some actors with each other came up. According to this concept, which reminds the 'pair programming' technique in agile software development, some actors are urged to solve specific design issues together before presenting a consistent design solution to rest of the actors. This practice would then force them to acquire greater responsibility for their solution in the long run. At the same time, from early organisational theorists as Olson et al. (1995), concurrent engineering is seen as a key activity to manage the tasks' dependences in design for constructability.
- In case B, the discussions evolved for a large part around the participation of the clients in the SC partnerships. The clients were deemed important in the partnering relation; to better understand the design and construction process and instigate innovation (Briscoe et al., 2004). This higher responsibility would then improve the trust and commitment (Min & Mentzer, 2004) and increase SC integration.

In conclusion, the 'internal validation' workshops validated the data analysis and findings, which was the primary goal of the sessions. The workshop participants recognised the analysis of the cases A and B, even though, at instances, it was not favourable and quite critical to the projects (case A). At the same time, the workshop participants reflected on how they have adjusted their way of working from project to project and provided more data for a post-hoc case analysis. This reflection helped to amend and improve some of the proposed strategies for SC integration. Overall, they validated and enriched the proposed strategies from Table 31 and Table 32 and in particular those at the strategic and tactical levels of decision-making. The workshop participants also emphasised on the compositions of the SC partnerships and especially of the architects and the clients, which is consistent with the findings in sections § 5.5, § 6.5.

§ 7.6 External validation

§ 7.6.1 Objectives of the Workshop on External validity

The external validity aimed at validating this doctoral research outside the research setting, i.e. the followed case studies. The external validity relates to generalisability and it aims at triggering the opinion of industrial domain experts about the research, so as to investigate to what extent the findings would be relevant to a larger part of the industry and potentially be transferable to other contexts. The domain experts were recruited to provide a pragmatic feedback about the research, beyond the confined boundaries of the academic and scientific world. Domain experts were considered individuals with a long-standing experience in the AEC sector, either from a professional, consultative or academic role or any combination of these three roles. After the workshop's completion, the research findings would be discussed and potentially validated or enriched by the experts.

The discussion with the experts was structured around questions based on statements of the research about (a) the theoretical synthesis, i.e. the two 'routes to integration' (see Figure 30), and (b) the operational framework, i.e. the proposed strategies for SC integration in AEC (see Table 31 and Table 32). The content of the section § 7.3 was the object of this validation session. The goal of posing these statements was to allow for comments and argumentation on the conditions under which the statements of the research would be applicable elsewhere. The discussions and the feedback from the experts were recorded and later transcribed. The outcome would be a set of statements about the extent to which the findings could be generalised. The participants chose to remain anonymous during the discussions in the 'External Validity' workshop. The relevant material, such as the workshop protocol, and discussion points are included in Appendix D. An additional secondary goal of the 'external validation' workshop was to collect additional data from the experts from the industry and potentially use them to enrich the proposed strategies and the operational framework, and for further research.

§ 7.6.2 Functions in the Workshop on External validity

The 'External Validity' workshop had similar structure and administration to the two 'Internal Validity' workshops. However, there were different roles for this workshop. In total four different roles participated in the Workshop: Facilitator, Researchers, Group of Experts, and Assistant. From those, the Facilitator, Researchers, and Group of Experts were active roles, whereas the Assistant had a supportive role pertinent to the organisation, recording, and general assistance in the session. The three active roles in the workshop had the following functions:

- *Facilitator*: The workshop facilitator was familiar with the PhD research but relatively impartial, and would use the workshop protocol to ensure that the discussions were heading in the right direction and that the time was managed appropriately. The facilitator would, for example, ask: "*Do you have any other comment/question about this last point*?", "*Could you give an example?*" and steer the discussion accordingly.
- *Researcher*: At the beginning of the meeting, the PhD researcher presented the research and the statements to be discussed. Afterwards, the PhD researcher was an observer of the discussions with the panel of experts, and ideally, would not intervene to defend the research, but only to explain or clarify.
- *Group of Experts*: The workshop was largely benefitted from the generous participation of experts and professionals active the construction industry, who were familiar with one or both of the main research topics, i.e. BIM and SCM, and possessed an academic mindset. Five of the experts were practitioners from the industry, from which three had more than 25 years of experience in the construction sector. These experts were selected as representative of the research target group, given that they had also been earlier contacted with the goal to assist the recruitment of case studies, which was however not deemed possible at that moment. Two of the experts were from a research and academic background, but with many years of engagement in 'contract research'. All experts had no formative role in the research and the researcher. To ease the discussions, it was preferred that the group of experts conferred in English. The experts and their abbreviations for quick reference (shown in parentheses) were the following:
  - Senior Researcher in Supply Chain in Construction (SC Researcher);
  - Senior Researcher in BIM (BIM Researcher);
  - Regional Director at a large contractor firm A (Contractor-Regional Director);
  - Project Leader at a large contractor firm B (Contractor-Project Leader);
  - Senior Consultant in Supply Chain integration (SC Consultant);
  - Business Development Manager at a Software Vendor (Software-Manager);
  - Senior Structural Engineer at a large consulting firm (Structural Engineer).

§ 7.6.3 Data collection and analysis method

The input for the 'external validation' workshop had a similar structure to the sessions on the 'internal validity'. The input was a presentation of a set of slides based primarily on synthesis (section § 7.3, Table 27, Figure 30, Table 31, and Table 32). Table 34 describes the presentation slides. Table 34 follows the same logic as Table 33 (see sub-section § 7.5.2) concerning the presented information of the thesis and the respective sections that the material is found.

TABLE 34 Organisation and content of the presentation slides for the input of the external validation' workshop.

PURPOSE	SLIDE NUMBER AND CONTENT	SECTION IN THE THESIS
Introduction	1. Complexities in the construction industry; 2. Research questions;	§ 1.1 and § 1.2 § 1.3
Background	3. Overview of the followed case studies in the Netherlands; 4. Rationale for focusing on the two polar cases;	§ 3.3, Figure 10 –
Analysis	5. Basic characteristics of the two polar cases 6. Contractual and digital information flow networks of the two cases	§ 3.3, Table 7 § 5.4, Figure 23
Synthesis	7. Synthesis of the factors for integrating BIM-enabled SC partnerships; 8. Two routes – 'actor-related' and 'product-related' – for achieving integration; 9. Proposed strategies to induce integration through the 'actor-related route'; 10. Proposed strategies to induce integration through the 'product-related route';	§ 7.3, Table 27 § 7.3, Figure 30 § 7.3, Table 31 § 7.3, Table 32
Closing	11. Information about the organisation of the discussions in the workshop; 12. Summary and main points for discussion	– –

The workshop took place June 6th, 2016, lasted two and a half hours and had the following structure:

- Arrival, welcome, and introduction of the participants (15 minutes);
- Opening and introduction (Facilitator) and distribution of hand-outs with the slides for personal notes (Assistant) (5 minutes);
- Presentation of the theoretical synthesis and the proposed strategies (Researcher) (5 minutes);
- Open discussion on selected proposed strategies (Facilitator and Experts) (120 minutes).
- The discussion was structured in sections of short discussions – fifteen minutes long – per proposed network strategy. In total eight strategies were discussed;
- Closing of the session and recapitulation of main points (Facilitator) (5 minutes).

Two research products were confronted with the group of industrial experts: (a) the two 'routes to integration' (see Figure 30), and (b) the operational framework, i.e. the proposed strategies for SC integration in AEC (see Table 31 and Table 32). The theoretical synthesis of the two 'routes to integration' was presented to the experts with the goal to be tested for refutability, i.e. investigate to what extent external observations and experiences carried from the experts could falsify the proposed theory. The operational framework, i.e. the proposed strategies for SC integration via the alignment of SC partnerships with BIM, was presented with the goal to be validated. The validation focused on (a) assessing the transferability of the research findings (Sarantakos, 2005, p. 86), (b) discussing the potential to generalise (Yin, 1984), and (c) efficiently utilising the generously offered knowledge from the panel's expertise, by adding more data and support to the proposed strategies. Recruiting the external panel of experts allowed the objective parties to assess the research (Miles & Huberman, 1994). The goal was to examine whether the findings and the components of the operational framework were supported by real-world practice and experiences in the Dutch AEC market.

Given the appearance of duplicate strategies across the two routes to SC integration from in Table 31 and Table 32, some redundant strategies were removed and the resulting versions of the tables are Table 35 and Table 36. At the same time, given the restricted duration of the external validation workshop, its structure utilised the expertise of the participants by channelling their industrial expertise into concepts that would trigger their interests. Within the text of the strategies some neutralised concepts from Table 28, such as 'BIM protocols', 'co-locations', 'trust', were highlighted and isolated during the presentation of the workshop. Subsequently, the experts would choose the concepts that were deemed more important to them, out of an array of concepts printed on 'post-it' papers, and in turn, the strategies that were associated with the respective concepts would be discussed. This process aimed to incite the active participation of the experts, increase their engagement to the goals of the workshop and their responsibility during the discussion. Figure 34 illustrates the two main set-ups of the workshop on external validity, i.e. (a) selecting the concepts (from an array of 'post-it' papers) and (b) discussing them. The bold text in and Table 35 and Table 36 indicates the neutralised concepts that would trigger the attention of the experts and direct the discussion accordingly, previously presented in Table 28.

FIGURE 34 The two main set-ups of the workshop: (left) selecting the concepts, and (right) discussing the strategies.

TABLE 35 Strategies for SC integration via the 'actor-related' route, after removing duplicates and accentuating with bold the neutralised concepts.

LEVEL	ACTORS -> PROCESS -> PRODUCT
Strategic	1. Issuing explicit formal **SC framework agreements** combined with elements of BIM protocols; 2. Partnering with firms with **integrated business models**, e.g. MEP firms; 3. Top management support for SCM adoption and **inter-organisational synergy**; 4. Adjustment of the **BIM scope and planning** to the SC's scope and commercial decisions.
Tactical	5. Establishment of **permanent contact persons** across the SC partnership; 6. **Early involvement** of the suppliers in the Design and Engineering phases; 7. Pre-scheduling frequent and time-wisely strategical **co-locations** for BIM collaboration;
Operational	8. Sharing a **collective future vision** for both BIM and SCM at a work floor level; 9. Encouragement of informal **communication across multiple tiers**; 10. Balance between the involvement of internal and external SC actors and **reciprocal interactions**; 11. SC partnership's flexibility and adaptability to obscure **phase boundaries**; 12. Increase of intra- and inter-firm communications to increase commitment and incite **trust**; 13. Digital information exchange of IFCs and proactive **informal communications** via ad-hoc means.

TABLE 36 Strategies for SC integration via the 'product-related' route, after removing duplicates and accentuating with bold the neutralised concepts.

LEVEL	PRODUCT -> PROCESS -> ACTORS
Strategic	14. Selection of BIM-savvy partners and **in-house BIM investment**, instead of outsourcing; 15. Alignment of the firms' **BIM readiness** with the SC partnership's BIM implementation level; 16. Partnering across firms with compatible **BIM** (internal or external motivation) **and SCM visions**; 17. Joint SC agreements about the **BIM protocols** and clear project/SC BIM scope; 18. Alignment of the BIM models with **local BIM specifications and National BIM policies**.
Tactical	19. Joint agreements on the BIM LODs and **clear design accountability**; 20. Clear designation of BIM coordinator and choice between the **proprietary or open deliverables**; 21. Inter-firm **BIM peer-learning and training**; 22. Elimination of the gap between **strategic and operational planning** at SC and firm levels.
Operational	23. Prioritisation among ad-hoc, linear, and distributed **BIM collaboration patterns**; 24. Information exchange of IFCs and provision of stable **physical and digital infrastructure**.

A limitation of this external validation strategy is that due to time and budgetary restrictions, only two and a half hours could be devoted to the external validation workshop. Thus, not all topics could be discussed, since the experts had time to select only a fragment of the proposed strategies. However, given that some of the concepts re-appeared across the various strategies, it would be possible that more than one strategy would be discussed per selected concept. Therefore, the structure of the 'external validation' workshop was deemed sufficient to validate and potentially enrich the proposed strategies for SC integration, given the available resources. The discussion was guided, but not limited to, by a set of options upon where the strategy could be applicable. These options were provided to give an idea and inspiration about the discussions. The options were the same for every strategy and investigated whether the proposed strategy was applicable to various other contexts, for example, the options were:

- this empirical research setting;
- repetitive projects;
- complex projects;
- small projects;
- large projects;
- mature supply chain partnerships;
- BIM-enabled projects;
- all projects.

For each strategy, if selected, the input for the discussion was of the following type:

"Is" + (Strategy from Table 35 and Table 36*) + "applicable to" + (options in bullet list above) + "?"*

§ 7.6.4 Experts' feedback on the theoretical Synthesis

The experts enjoyed the discussion about two routes to reach SC integration, as presented in Figure 30. First, the Software-Manager asked: *"is BIM related only to the 'product-related' route (...) and SCM only about collaboration and actors, but not about logistics?"*, which was an accurate observation based on the conclusions of Chapter 2 (see section § 2.7). After reflecting on the theoretical grounds that allowed for these deductions (see Chapter 2), the experts started reflecting on which route could be most valuable for SC integration. The Structural Engineer noticed that the 'product-related' route might have a faster take-off, but was not convinced of its appropriateness for SC integration. The BIM Researcher, the SC Consultant, and the workshop Facilitator agreed that the 'actor-related' route would be more appropriate for SC integration:

"the 'actor-related' route has more impact because it attaches to the strategic SC vision. But which one would have more impact on the results? It is not the goal only to implement BIM but to enhance the performance of the SC" (SC Consultant).

The workshop Facilitator emphasised that BIM has to be intensively implemented to reap its benefits, however for SC integration, BIM is not enough, and the two routes could be adopted in parallel.

§ 7.6.5 Experts' feedback per strategy

The strategies of Table 35 and Table 36 were numbered to facilitate the referencing to the respective strategies. From the workshop structure, the expert panel chose to discuss eight strategies, based on the concepts of integrated business models (2), inter-organisational synergy (3), early involvement (6), co-locations (7), trust (12), BIM readiness (15), BIM protocols (17), and BIM collaboration patterns (23) (see Table 35 and Table 36). Whereas these eight strategies are only a small fragment of the total number of proposed strategies (n=24), the discussion occasionally steered away from the respective strategies and was tangential to other strategies presented in Table 35 and Table 36. Overall, all strategies from Table 35 and Table 36 emerged during the discussions to some extent. Table 37 presents how the various concepts and strategies were intermingled during the discussions of the external research validation workshop with the experts. The data from the various strategies will be presented next following the categorisation into strategic, tactical, and operational hierarchical levels.

TABLE 37 Discussed strategies for SC integration during the external workshop and tangential concepts that emerged during the dialogue among the experts.

DISCUSSED CONCEPTS AND STRATEGIES	EMERGING TANGENTIAL CONCEPTS AND STRATEGIES
integrated business models (2)	SC framework agreements (1), inter-organisational synergy (3), early involvement (6).
inter-organisational synergy (3)	BIM scope & planning (4), BIM & SCM visions (16), strategic & operational planning (22).
early involvement (6)	SC framework agreements (1), BIM scope and planning (4), communication across multiple tiers (9), BIM & SCM visions (16).
co-locations (7)	BIM scope & planning (4), reciprocal interactions (10), trust (12), in-house BIM investment (14).
trust (12)	BIM scope & planning (4), permanent contact persons (5), co-locations (7), collective future vision (8), informal communications (13), BIM & SCM visions (16), clear design accountability (19).
BIM readiness (15)	BIM scope & planning (4), BIM & SCM visions (16), BIM peer-learning & training (21), BIM collaboration patterns (23).
BIM protocols (17)	SC framework agreements (1), inter-organisational synergy (3), BIM scope & planning (4), communication across multiple tiers (9), phase boundaries (11), BIM & SCM visions (16), local BIM specifications & National BIM policies (18), proprietary & open deliverables (20).
BIM collaboration patterns (23)	BIM readiness (15), proprietary & open deliverables (20), physical & digital infrastructure (24).

Contribution of integrated business models and strategic visions to SC integration

In principle, the experts agreed that having integrated business models, such as with MEP firms, could induce SC integration. For the SC Consultant, this strategy reminded of the "*automotive industry where having small suppliers integrated within larger firms could reduce cost and also boost innovation*", such as the adoption of BIM. However, he pointed out that this would have to align with top management support and inter-organisational synergy (Table 35, strategy #3) and that potentially it would be applicable only to mature chains, where there is "*fusion of interests*" (SC Consultant). In the same spirit, the Structural Engineer noticed that "*simply buying a company does not mean that it becomes an integrated firm*." For the Contractor-Regional Director, the practical applicability of the proposed strategy was only to large projects, because he did not see the reason "*to make the SC shorter*." He acknowledged that for reducing costs it would be good, but "*it is very difficult to make such a transparent agreement with the client and the suppliers, because, the customer is valued higher than the supplier*' in his company (Contractor-Regional Director). He explained how they essentially involve the suppliers earlier (Table 35, strategy #6), but not with explicit SC framework agreements (Contractor-Regional Director). A counter-argument for this problem was as to the case of repetitive housing projects, where "*there is a shared SC proposition among all suppliers and client*" as SC framework agreements (Table 35, strategy #1), which could essentially bypass the dilemma of choosing between client and supplier (SC Researcher).

Contribution of inter-organisational synergy, leadership, and BIM to SC integration

All experts agreed that the strategy about inter-organisational synergy for inducing SC integration was applicable to all projects. However, "*it is most difficult to get the SCM vision to the work floor because it is a behavioural change*" (Contractor-Regional Director). Thus, for the chain's commercial decisions, a joint SC strategic and operational plan (Table 36, strategy #22) would be additionally necessary, so as to ask "*from your partners' work floor, what your work floor can also do*" (Contractor-Regional Director). The remaining time of the discussion focused on leadership and BIM adoption. The existence of a "*shared vision for BIM (...) is what drives to share information and optimise and improve the workflow*" (SC Consultant) (Table 35, strategy #6). However, the experts highlighted that to align the BIM scope and the planning (Table 35, strategy #4) across the SC partnership, "*leadership is needed for the implementation of decisions of the top management, and the ability to 'lead by example'*" (SC Consultant). The Structural Engineer underscored that "*the problem is mostly in middle management*" and the workshop facilitator concurred that "*all innovations stop in the middle management*." The Contractor-Regional Director added that "*when the workers are working on BIM very well, the middle management might not be needed after all*," because the process becomes more transparent and easy to manage. The discussion then was steered to a topic at the sideline of the research and in particular on the importance of the strong prior technical experience of the top managers. The experts agreed on that:

"The art of building a virtual company is not purely a technical skill, but also a more soft competence, how to combine people into an efficient team. Nowadays we need more

soft competences for a manager, for a balanced combination, because it is too much technical and less organisational" (SC Consultant).

The Structural Engineer also added that an 'open mind' might be good for leading change management in a firm, given that outdated engineering skills might also hinder innovation and change management.

Contribution of early actors' involvement and contractual relations to SC integration

There were two contradictory opinions about the application areas of the strategy on early supplier involvement. The SC consultant and the BIM Researcher agreed that this strategy could lead to SC integration if the supplier would be treated as 'co-designer', and would improve the project outcomes. When the suppliers are truly treated as 'co-designers' then indeed the communication could expand across multiple tiers (Table 35, strategy #9). However, the Contractor-Regional Director was of the opinion that "*the early involvement is good for the design phase and the engineers*", but not for the realisation phase, as in his company, they "*separate the design from the realisation phase*" and essentially handle "*two different supply chains*". The facilitator then stressed that "*only if the suppliers are critical for the project, they could be involved earlier*." This argument again resonates with the discussions about the compatibility of the BIM and SCM visions among the SC partners and to what extent SCM and BIM mean the same things for various partnerships (Table 36, strategy #16). Another condition for the engagement to early involvement of the suppliers could be the alignment of BIM with the project scope and planning (Table 35, strategy #4), as "*if the project does not fit to one particular SC, they could adjust either the design or change the SC*" (Contractor-Project Leader). The Structural Engineer highlighted that there might be contractual issues concerning the SC framework agreements and sharing information about BIM (Table 35, strategy #1), with the SC partners. Similarly, the SC consultant highlighted that the early involvement could take place in "*mature strategic partnerships, they should, where they have to pay the suppliers for their advice under an incentive scheme*."

Contribution of co-location practices, BIM investment, and BIM visions to SC integration

Overall, the co-location practices were deemed supportive of SC integration from the experts. However, there was a disagreement about whether it was more applicable to mature SC partnerships or not. For the SC Researcher, it seemed to be less needed in mature partnerships, because "*after 200 projects you get to know each other*", whereas for the Contractor-Regional Director, it was more applicable to the mature SCs, as there was also a need for underlying compatible BIM and SCM visions (Table 36, strategy #16) and trust (Table 35, strategy #12). At the same time, the co-locations had to be in accordance with the "*vision about the scope you want to get with BIM*" (Contractor-Regional Director) (Table 35, strategy #4). For the Contractor-Project Leader, the co-location practices would be supportive of SC integration in all projects. However, he pointed out that the interactions had to genuinely reciprocal among the actors (Table 35, strategy #10), otherwise "*some people sit together but do not work together*". The Structural Engineer brought up another important aspect of this strategy, which related to the strategy about BIM investment (Table 36, strategy #14), and particularly because "*usually the architects do not have a laptop, who pays for those and the rent for the location of the co-locations?*". In an effort to overcome this financial barrier, the SC Researcher counter-proposed the option of "*digital co-location*" instead, which was refuted by the Structural Engineer: "*It is possible, but it is more difficult. In a digital setting, you do not have 'small talk'. I think the co-locations can be useful in all projects, but it is most beneficial to practice that in small projects first*".

Contribution of trust, communications, and hierarchical levels to SC integration

As concerns the extent to which trust and increased communication could support SC integration, this was considered having a positive linear relationship, but according to half of the expert panel, only under certain content-related conditions. On the one hand, for the Contractor-Project Leader and the Software-Manager, all types of intra- and inter-firm communications under complete transparency could incite trust. Moreover, the Contractor-Project Leader and the BIM Researcher added that probably post-hoc "*project validation process*" would be supportive of SC integration, as "the trust on the quality of information is also important" (Contractor-Project Leader). The Contractor-Project Leader discussed an example where they could not trust the BIM model provided by the architect and he pointed out that having clear design accountability was also critical to achieving trust and incite SC integration (Table 36, strategy #19). The Contractor-Regional Director also agreed with the previous statement and highlighted that "*we should not talk only about the bad things. We forgot to do talk about the good things, like our shared vision*" (Contractor-Regional Director). Then, he suggested having compatible BIM and SCM visions at a strategic level (Table 36, strategy #16) and "*same vision at a work floor*" (Contractor-Regional Director) (Table 35, strategy #8).

On the other hand, for the SC Consultant, not all communications could support SC integration, e.g. "*discussion about price, contracts, and (poor) quality of work do not help to build trust*". *Discussing the interpretations around a bad contract is bad*" (SC Consultant). It was also pointed out that probably "*after a good SC collaboration, you need less communication from process standardisation, as everything is aligned by then*" (SC Consultant) because of having permanent contact persons (Table 35, strategy #5). The Structural Engineer underlined that the increased communications "*in the early stage are more important to set the common BIM goals and planning*"

(Table 35, strategy #4), as "*then you see from the beginning the gaps that you face, and then you can resolve them half-way. You have to start with a good 'kick-off' to resolve it early*" (Structural Engineer). The SC Consultant also pointed out that "*since there is a weaker relation between tools and trust, and trust is more personal, then the trust is high in co-locations practices*" (SC Consultant) (Table 35, strategy# 7).

Contribution of BIM readiness and strategic partners' selection to SC integration

Regarding the strategy of aligning the BIM readiness levels with the BIM implementation level of the SC partnerships, all experts agreed on principle. However, another provocative proposition at the sideline of this strategy emerged and was discussed: as to what extent the exclusive alignment among firms with similar levels of BIM maturity would be a desired strategy for SC integration. For example, the Contractor-Regional Director stated that for firms with an under-developed level of BIM, such alignment could also be good, because they could counterbalance their deficiencies from BIM peer-learning and training (Table 36, strategy #21). For the Software-Manager and the Contractor-Project Leader, "*theoretically, it could be the best option. In practice it will not be*" (Software-Manager) and "*the aligned SC on the same level is utopia, but I agree this alignment has to take place beyond a project-level*" (Contractor-Project Leader), which again relates to the discussions about setting up joint scope and planning decisions with BIM (Table 35, strategy #4). The BIM Researcher strongly opposed the alignment of firms based on BIM maturity, by posing the argument that some companies, e.g. the "*concrete supplying companies do not need the same criteria to collaborate with BIM as other actors*". The previous argument was refuted by the SC Consultant, who proposed that concerning compatible BIM and SCM visions (Table 36, strategy #16), the "*SC will be weak if the strategic partners are not well advanced in BIM, so the BIM alignment of strategic partners is very important for the integration*" (SC Consultant).

Contribution of BIM protocols and SC scope to SC integration

In principle, all experts agreed on the necessity of BIM protocols for inducing SC integration. However, over the course of the discussion, it was made clear that not all experts agreed on the definition of the 'BIM protocols' as the prescriptive document issued by the Dutch GBA (Rijksvastgoedbedrijf), or the usability of local BIM specifications and National BIM policies (Table 36, strategy #18). For example, for the Contractor-Regional Director, the BIM protocol pertained more on the file format of information exchange, e.g. open or proprietary deliverables (Table 36, strategy #20), while the Structural Engineer viewed them as prescriptions of processes. The Contractor-Project Leader emphasised that the BIM protocol "*is more than exchanging files*" and that it relates to the BIM scope and planning (Table 35, strategy #4). At the same time, it was stressed that in practice the BIM protocol "*has nothing to do with* *the project management plan, because it is not drafted by the person who manages the project*" (Contractor-Project Leader). Thus, whereas the BIM protocols are needed at a strategic level, the tactical level has to be on board, because of the obscure phasing to:

"customise the BIM protocol to the engineering process and the planning and the organisation of the project. We usually do not discuss the protocol properly. (…) First, we should have the logistics planned, decide if BIM can help, and then have a protocol" (Contractor-Project Leader).

The BIM Researcher agreed that the "*protocols are made from people who do not know anything about the SC. (…) The SC integration happens from clear BIM scope rather than just the BIM protocol*". To support these discussions the Structural Engineer stated that as the project phase boundaries are obscure at the beginning of the project (Table 35, strategy #11), the BIM protocol should be flexible, and you have to "*update the BIM protocol along the way*". Similarly, the SC framework agreements (Table 35, strategy #1) should also be flexible "*from the beginning when you do not already know the suppliers; there are contractual issues*" (Structural Engineer). The BIM Researcher also emphasised that an inter-organisational synergy (Table 35, strategy #3) is needed, as forcing BIM protocols to the SC, will not be efficient eventually and "*we probably need different protocols in each project*" (BIM Researcher).

The latter was essentially the opposite strategy from the Contractor-Regional Director, who had one protocol incorporated with the SC framework agreements that they signed with their suppliers (Table 35, strategy #1). According to their strategy, through pre-defined BIM protocols, they communicate their BIM and SCM visions (Table 36, strategy #16) across multiple tiers (Table 36, strategy #9), to "*tell people what they look for in the SC partnership*" (Contractor-Regional Director). The Software-Manager also concurred with this strategy for BIM implementation. The SC Consultant agreed that "*agreeing on a strategic level about the BIM protocols could reduce costs*" and wondered whether a "*joint industry protocol would be ideal (…) from the agreements of big companies coming together*". The later does not only resonates with the proposition for local BIM specifications and National BIM policies (Table 36, strategy #18), but also recent developments in the Netherlands towards this direction.

Contribution of BIM collaboration patterns and communications to SC integration

The experts recognised all three patterns of ad-hoc, linear, and distributed BIM collaboration from their experiences in settings outside of this empirical research, as defined in Chapter 3. The discussion then evolved around the identification of the extent to which choosing among those three patterns could induce SC integration. The SC Consultant highlighted that the maturity of the SC partnership also plays a role in SC integration. By focusing only on the ad-hoc BIM collaboration pattern, all experts agreed that it "would induce chaos" (Software-Manager) that "*it has less value than the traditional design process*" (Structural Engineer) and that "*You usually do not want your people to work on such projects*" (Contractor-Project Leader).

Regarding the linear BIM collaboration pattern, the Contractor-Project Leader and the Software-Manager concurred that as these are "*essentially like data-drops*" (Contractor-Project Leader), they could "*support BIM implementation but would not be good for SC integration*" (Software-Manager). The BIM Researcher noticed that for the "*BIM maturity of the SC partners the linear and ad-hoc patterns would be efficient but not for the SC integration*" (Table 36, strategy #15). The latter resonated with the claims of the Contractor-Regional Director, that "*with BIM it is all of nothing. You cannot choose to do it a little bit, like you can do with SCM*" and admitted that they "*do a lot of linear collaboration in their firms*" as it complicates the implementation of SCM.

The Software-Manager and the BIM Researcher identified similarities between the distributed BIM collaboration pattern and the UK BIM Maturity Level 2. The Software-Manager emphasised that this collaboration pattern could support SC integration in all projects. They also linked it to the discussions about prioritising between open and proprietary deliverables (Table 36, strategy #20) for different phases of the design development and among various actors. The Contractor-Project Leader admitted that the appropriate physical and digital infrastructure (Table 36, strategy #24) to support the distributed BIM collaboration pattern, or the "technology stuff is in place":

"For the distributed pattern we have to learn to work with all the parties. Maybe we should now do things differently. The distributed pattern entails redesigning the processes. It takes a long time, and everyone has to be very transparent about what we mean with BIM and how to be efficient." (Contractor-Project Leader).

Finally, the SC Consultant underscored that similarly with SCM "*there is a lot of opportunistic behaviour in the construction industry about BIM, and many say they are mature, whereas they are very traditional*" (SC Consultant).

§ 7.6.6 Reflection from the Workshop on External validity

Overall, the discussions with the external experts offered two main ameliorations to the research products, i.e. the operational framework of proposed strategies: (a) sharpened and enriched some of the strategies, and (b) validated the transferability of the proposed strategies outside the empirical setting of the cases, and particularly in the Netherlands. Most of the incongruent opinions stemmed from the varying backgrounds of the experts, either industrial and research or SCM- and-BIM-related backgrounds.

However, the cumulative impact of the discussions offered a healthy combination of practical and theoretical knowledge, as well as a more pragmatic view on the two research products of this PhD research. A quite inconclusive (partial) validation pertains to the categorisation of the proposed strategies under the strategic, tactical, and operational hierarchies; of the eight discussed strategies, only one strategy, namely the one on 'BIM protocols,' was deemed misplaced as to its categorisation into the STO decision-making hierarchy. The summary of main discussion points from the external validation phase will be presented as clustered around three thematic areas, the (a) hierarchical levels, (b) SCM practices, and (c) BIM protocols and processes.

Concerning the hierarchical levels, the concept of 'top management engagement' could replace the concept of 'top management support' so as to pertain to the leadership skills that the top managers need to possess to promote organisational change (Lambert et al., 1996). Accordingly, as Lambert et al. (1996) claimed, the active support and engagement of a company's top managers as "change agents" could incite greater commitment of the work floor to innovation change management. Another observation pertinent to the hierarchical levels was on the relation between innovation change management and middle managers in organisations or the so-called 'tactical or administrative' level. For Winch and Kelsey (2005), the project planners (tactical level) apart from the planning tasks, have to manage many soft aspects as well, such as negotiation and communication. This again echoes the debate of a task-oriented or organisational-oriented project manager (Andersen, 2016). It is commonly believed that the middle management could 'make or break' an innovation change and that the middle management acts as a bottleneck to the adoption and diffusion of innovation at an intra-organisational level. Often the middle management is even more influential for instigating change in an organisation, rather than specially appointed firm-based innovators (Mollick, 2012). The latter is also consistent with findings of Forgues and Lejeune (2015), about the both technical and organisational skills that are preeminent for the project managers in the new digital era of construction, and particular after the introduction of BIM. Likewise, BIM-related skills are increasingly required for construction managers (Gathercole & Thurairajah, 2014), given that some of the built-in capabilities of BIM, facilitate transparency in the management of time, quantity, and cost in a construction project (Eastman et al., 2008; Bryde et al., 2013). Therefore, BIM challenges the traditional hierarchies in construction project management.

The most provocative statement throughout the discussion of the external validation workshop was the disclosure that in the one of the contractor firm, they "separate the design from the realisation phase" and essentially handle "two different supply chains". This practice contradicts the literature on achieving integration in construction, by following strategies to integrate either the multi-disciplinary actors involved in construction (Nam & Tatum, 1992) or the various processes (Howard et al., 1989). After all, Vrijhoef and Koskela (2000) claimed that the focus on "transferring activities from the site to the supply chain" could reduce the inter-organisational and processual interfaces and integrate the construction SC. In the same spirit, the suppliers could acquire a more dominant role in the design process, and act instead of only as supplier additionally as 'co-designers' (Nederveen et al., 2010). After all, close – beyond contractual and project boundaries – relationships between designers and suppliers could increase the transfer of technical capability (Sariola & Martinsuo, 2016). Thinking about the suppliers as 'co-designers' also emerged in the discussions and particularly in the context of BIM, as the supplying companies do not need the same BIM maturity to collaborate with BIM as equals as other actors, such as the engineers. Various studies have corroborated the dynamic role that the suppliers could play during the multi-actor BIM collaboration in design and engineering phases (Berlo et al., 2012; 2015; Berlo & Papadonikolaki, 2016). Accordingly, the BIM-enabled SC partnerships could choose either to align with the BIM readiness of their strategic actors or engage in early involvement with non-strategic actors, by issuing an incentive scheme for their advice to "recognise and reward cooperative behaviour" and potentially inspire higher performance consistency (Lambert et al., 1996; Gosling et al., 2015) . Another SCM practice at the periphery of the discussions, pertained to the enrichment of communications not only with project-related content but also with 'project validation' or as found in SCM literature, performance and benchmarking reviews (Bemelmans et al., 2011) that could result in SC improvement and promote SC integration.

The only discord during the discussions on external validity about the categorisation on the strategic, tactical, and operational levels pertained to the BIM protocols. As emerged from the empirical data from Chapters 5 and 6, there was an abundant need to align the BIM protocols with the scope of the projects but also of the SC partnerships, e.g. regarding planning and division or work. In the strategies, it was proposed that the BIM protocols would be better prepared at a strategic level. However, according to the experts, currently the BIM protocols are prepared at a tactical level, but nevertheless, lack consistency and rarely follow the actual needs of the projects. Therefore, there is a need for a flexible way of issuing the BIM protocols, across all intra- and inter-organisational levels. The National prescriptions for BIM protocols or 'BIM Execution Plans' do not specify the function of the person responsible for issuing them, neither in the UK version (CPIc, 2013), the Dutch equivalent (Rijksgebouwendienst, 2012), or the Norwegian antecedent (Statsbygg, 2011). Therefore, and given that the local construction market has already proven their capability to self-regulate by enriching and complementing the National BIM policies, e.g. by agreeing on common BIM-related specifications (Berlo & Papadonikolaki, 2016), probably the BIM protocols need input from multiple sources (and potentially multiple intra-organisational roles), such as:

- National BIM policies (mandatory or prescriptive),
- Local industry's initiatives and agreements,
- Strategic inter-organisational levels, e.g. contractual elements and
- Tactical intra-organisational levels, i.e. at a project management level.

These multiple sources, whose input is required for a BIM protocol, suggest that probably the BIM protocols have to bridge complex gaps at a policy level, before being consistent at a project level and efficient at an inter-organisational network. Regarding the BIM collaboration patterns, presented in Chapter 3, those were treated with enthusiasm by the experts and corroborated that the *distributed* pattern is probably equivalent to the UK BIM Maturity Level 2 (Papadonikolaki, Vrijhoef, & Wamelink, 2015). They added that to collaborate efficiently with BIM, the firms would potentially have to redesign their processes, but also think about the involved actors and the product-related details of the exchanged information.

After the discussions of the 'external validation' workshop, the strategies presented in Table 35 and Table 36 were improved and enriched. Table 38 and Table 39 present the same strategies as Table 35 and Table 36 and have an additional column to the right which contains the outcome of the validation. In the last column to the right, there are three types of outcomes: (1) 'Yes', (2) 'Inc', and (3) 'Con'. These outcomes stand correspondingly for: (1) discussed and approved strategy (Yes), (2) inconclusive discussions (Inc), and (3) conditional applicability of the strategy including the condition (Con). For example, regarding strategy#1 (see Table 35), all experts from the 'external validation' workshop agreed that this is a feasible strategy to induce SC integration. Concerning strategy#2 (see Table 35), the experts concurred that this strategy would be applicable only to large projects. Similarly, about strategy#4 (see Table 35), the discussions were steered towards the function of the project manager, and to what extent their background, could influence their perception of the project and the firms' commercial decisions. Other strategies, such as strategy#5 (see Table 35), were deemed inconclusive, as the research design of the validation session and the time allotted for discussions was not enough to expand on this topic.

TABLE 38 Strategies for SC integration via the 'actor-related' route, including the results of the validation.

LEVEL	'ACTOR-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUTCOME
Strategic	1. Issuing explicit formal SC framework agreements with elements of BIM protocols;	Yes*
	2. Partnering with firms with integrated business models, e.g. MEP firms;	Con*: large projects
	3. Top management support for SCM adoption and inter-organisational synergy;	Con: engagement
	4. Adjustment of the BIM scope and planning to the SC's scope and commercial decisions.	Con: project manager
Tactical	5. Establishment of permanent contact persons across the SC partnership;	Inc*
	6. Early involvement of the suppliers in the Design and Engineering phases;	Con: trust
	7. Pre-scheduling frequent and time-wisely strategical co-locations for BIM collaboration;	Yes
Operational	8. Sharing a collective future vision for both BIM and SCM at a work floor level;	Con: clear BIM scope
	9. Encouragement of informal communication across multiple tiers;	Yes
	10. Balance between internal and external SC actors and reciprocal interactions;	Con: co-locations
	11. SC partnership's flexibility and adaptability to obscure phase boundaries;	Inc
	12. Increase intra- and inter-firm communications to increase commitment and trust;	Yes
	13. Digital information exchange of IFCs and proactive informal ad-hoc communications.	Con: trust

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

TABLE 39 Strategies for SC integration via the 'product-related' route, including the results of the validation.

LEVEL	'PRODUCT-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUTCOME
Strategic	1. Selection of BIM-savvy partners and in-house BIM investment, instead of outsourcing;	Inc*
	2. Alignment of the firms' BIM readiness with the SC partnership's BIM maturity level;	Yes*
	3. Partnering across firms with compatible BIM (internal/external drive) and SCM visions;	Inc
	4. Joint SC agreements about the BIM protocols and clear project/SC BIM scope;	Con*: BIM manager
	5. Alignment of the BIM models with local BIM specifications and National BIM policies.	Yes
Tactical	6. Joint agreements on the BIM LODs and clear design accountability;	Con: trust
	7. Clear role of BIM coordinator and choice between proprietary or open deliverables;	Yes
	8. Inter-firm BIM peer-learning and training;	Con: clear BIM scope
	9. Elimination of the gap between strategic and operational planning at SC and firm levels.	Con: project manager
Operational	10. Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns;	Yes
	11. Information exchange of IFCs and provision of stable physical and digital infrastructure.	Con: clear BIM scope

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

§ 7.7 Chapter recapitulation

This chapter had a twofold goal; first to present the synthesis of the research, and second to discuss and validate it. Regarding the synthesis, it consisted of two components: (a) a theoretical synthesis and (b) a model of proposed strategies for BIM-enabled SC partnerships. First, for the theoretical synthesis, the findings that were part of the discussion sections in Chapters 3 to 6 were systematically combined in a tabulated form to represent the factors that could contribute to integration as derived from the empirical data. These findings were categorised according to the taxonomy of the P/P/A conceptual framework from Chapter 2 and according to the STO hierarchical levels. Afterwards, these factors were confronted to the set of polar cases that was analysed in depth. From their gap analysis, it was deduced that throughout the empirical setting of this thesis, there were two main routes to achieve SC integration: a 'product-related' and a 'process-related' route. *Accordingly, for each one of these routes, a model of concrete strategies which could induce SC integration in BIM-enabled SC partnerships – utilising the P/P/A dimensions and the STO levels – was proposed* (answer to RQ#6).

The research products of this thesis were apart from proposed, also discussed in the form of three consecutive validation steps. First, a 'construct validity' session took place at an academic conference to evaluate the initial methodological decisions and the relations between the two main constructs of the study, i.e. SCM and BIM. From this 'construct validity' session, it was concluded that the main research limitations of this PhD research are located in the a priori choice of the employer (MBE department, see section § 1.1) to investigate the concepts of SCM and BIM simultaneously, and the lack of convincing research motivation for this choice. Also, the fact that this thesis is at the intersection of engineering and social sciences (management) and that the researcher, is an engineer and not a social scientist, might, of course, entail some implicit biases. However, especially, because the thesis is at the intersection of engineering and social sciences, more validation steps were performed. Second, an 'internal validity' session took place among the case participants of the two polar cases. The goal of this session was to evaluate to what extent the researcher's observations and analyses were consistent with the research findings. Indeed, the case participants concurred that they 'recognised the patterns' of their projects to the analysis. At the same time, some new concepts and suggestions emerged from the discussions. Namely, the concept of 'concurrent engineering' has started to play an important role in the BIM-enabled SC partnership of Case A, whole the SC of case B was more interested in the 'demand' side of the SC and particularly in the participation of the client.

Finally, from the 'external validity' session, additional external remarks were obtained about the two research products of this thesis, (a) the theoretical synthesis, and (b) the proposed strategies. The goal of this session was to evaluate to what extent these research products were transferable to other contexts or applicable to other projects and potentially offer new insights (and data) into the conditions for the popularisation of the phenomenon of BIM-enabled SC partnerships. Overall, the discussions in the 'external validity' session revolved around three thematic areas, the (a) hierarchical levels, (b) SCM practices, and (c) BIM protocols and processes. First, it was deemed germane that the tactical level would have to play a new and enhanced role in the intra-organisational synergy, which SC integration requires for the diffusion of integrative visions in BIM-enabled SC partnerships. Second, the genuine engagement of the top management in non-opportunistic behaviour and use of incentive schemes could also be a parameter for strengthening SC integration. Third, the BIM protocols were deemed a really hot topic during the workshop, as the panel of experts was essentially divided into two parts: one for and one against the use of SC-based BIM protocols with contractual strength. Eventually, these three consecutive validation steps laid down the ground for the reflection, limitations, and outlook of this PhD thesis.

8 Reflection, Conclusions, and Outlook

Chapter summary

Whereas SCM and BIM have in the past been identified as a promising management philosophy and set of technologies respectively for the AEC industry, both terms have been quite ill-defined conceptually in practice and academia. At the same time, and while the two concepts could be considered compatible in nature, their real-world combination has rarely taken place in practice, and there is a lack of empirical evidence of this combination. This dissertation has analysed empirically (Chapter 3), conceptually (Chapter 4), pragmatically (Chapter 5), and theoretically (Chapter 6) the potential repercussions from the combination of SCM and BIM, and attempted to contribute to their alignment and popularisation by analysing and recognising their compatibilities and interdependences. Afterwards, a set of strategies for achieving integration in AEC through their combination was proposed and validated (Chapter 7), following the P/P/A framework, from Chapter 2, across the STO levels.

The contribution of this research has been primarily the focus on analytic and interpretative approaches, regarding their effects on a multi-actor construction network. Overall this PhD research approached the SC system as a network of actors, using theories and tools for exploring and analysing BIM and SCM as integrative innovations. The future steps of this research could be directed towards covering limitations and aspects not considered before, such as focusing on the material flows of the SC, the exploration and application of BIM-enabled SC partnering to industrialised construction, e.g. 'concept-houses', or the extension of the research towards the early and late phases of the AEC lifecycle, i.e. initiation and operation until maintenance, and actors not dominant in the present study, e.g. clients and owners. Ultimately, BIM and SCM as integrative approaches could be linked to the recently resurfaced debates about the broader sense of sustainability as a strategy to reduce costs and increase efficiency, as well as re-visiting Systems Thinking and considering the Built Environment as an open-ended network rather than a linear and deterministic chain.

§ 8.1 Reflection and general Discussion

§ 8.1.1 The interplay between SCM and BIM

Whereas SCM and BIM have been previously identified as a promising management philosophy and a set of technologies respectively, both concepts have been quite ambiguous and treated either with blind conviction or severe scepticism. This phenomenon was caused first by the ill-defined theoretical grounds of SCM (London & Kenley, 2001), and second due to BIM being a contemporary buzzword for the construction industry. On the one hand, SCM has been heavily criticised in the past for being not only ill-defined (London & Kenley, 2001), but also inessential (Fernie & Tennant, 2013), and harmful to the free competition in the market (Briscoe & Dainty, 2005; Green et al., 2005). In other industries, SCM continues to be of relevance and an ever-growing field of research, for either optimising and managing the uncertainties or for studying the coordination and behaviour of the SC firms (Chan & Chan, 2010). Apart from the mere logistical interpretations of the SCM in other fields, the relational perspective of SCM is also quite popular (Leuschner et al., 2013; Kembro, Selviaridis, & Näslund, 2014), and in particular with regard to building trust and deploying contractual means.

On the other hand, whereas BIM symbolises a long-standing effort for the standardisation of building information (Eastman, 1999) – with 'BIM' being only its latest 'fancy' nickname – it was only until recently that it became a key focus of construction management research. For example, despite that these efforts started as early as 1994, when the IAI was founded (Bazjanac & Crawley, 1997), it was only after the mandatory character of BIM with the PAS 1192 in the UK that BIM was – unavoidably – accepted, but yet not genuinely embraced by construction management researchers. This paradox is a proof that the gap between academia and industry is still quite persistent, but also that the innovations in AEC are –sadly –usually democratised after 'top-down' policies rather than 'bottom-up' and self-organised industrial initiatives. At the same time, another pertinent criticism relates to the lack of a holistic consideration for construction IT. Given that BIM will soon undoubtedly become an industry standard, it is usually seen as a panacea for all problems. However, what is still missing is the acknowledgement of the 'big picture' and that BIM is yet another articulate acronym to describe a set of construction IT, as well as that probably:

"in a couple of years, we will see BIM as a funny word that we used while we were in a transition between a paper-based industry to a data-driven industry"[13].

13 Comment made by the Senior BIM Researcher during the 'external validation' session on June 6th, 2016 (see section § 7.6).

Despite the shifting emphasis towards BIM, the most prominent discussions about its applicability and benefits focus on the intention to leverage from it in the FM area, and thus towards the end of building's lifecycle. In her inaugural lecture on May 25th, 2016 Professor Jennifer Whyte, who views the construction industry from a Systems' Engineering perspective, focusesd on the role of the client and on managing the requirements for future facilities (Whyte, 2016), by highlighting the benefits of information management for the construction lifecycle. With regard to BIM and the latest stages of the construction lifecycle, existing research has underlined that there are indisputable technical challenges for the BIM/FM integration (Korpela et al., 2015). Lately, the discussions around BIM are linked to, another key buzzword of our times, 'Big Data' presuming that the analysis and management of COBie files – a spreadsheet translation of the IFC created by Bill East (2007) – could induce benefits to the construction client. However, COBie, which is avidly supported by the UK PAS 1192-2 specifications, is already an almost obsolete solution for building data management. Moreover, this emphasis on BIM for FM and the client-focus probably inevitably requires a – new – definition of the client, whether it refers to the 'professional', 'public' or 'large-scale developer'. After all, traditionally in construction there are fewer experienced clients than in other sectors (Morris, 2004). Another consideration, inevitably, is the exclusiveness of such valuable services to 'prominent' clients as opposed to the services delivered to the rest – less prominent clients, e.g. SMEs – that still affect the Built Environment with their commercial decisions.

Rather than focusing primarily on the client and demand management and bypassing the problems and potential solutions to the innate collaboration and coordination complexities of the construction industry, this thesis has focused on the collaboration and coordination of the multi-actor construction networks. Therefore, it is argued that the emphasis should not completely shift to the demand side of the SC, rather than attempt to achieve a synergy between the two parts of the construction SC, demand and supply side. In this context, it is then quite ironic that BIM – and its implications for the SC – came into the spotlight at a moment where the SCM- and collaboration-related visions were already discredited as a bad fit for the construction industry, despite being envisioned from Sir Egan's Report (1998) in the UK almost two decades ago. Undoubtedly, BIM has come to teach the industry something about collaboration and coordination beyond organisational boundaries, and this could subsequently make SCM philosophy relevant again.

§ 8.1.2 The alignment of SCM with BIM

One of the greatest challenges during the three and half years of this PhD research on the '*Alignment of SCM with BIM*', was the suspiciousness that both SCM and BIM concepts generated across various audiences of construction management research. The simultaneous implementation of both SCM philosophy and BIM technologies has been seen as the most dubious – or even mythical – practice for construction practice and research, and particularly for audiences outside the Netherlands. Very few audiences believed its real-world existence, and even fewer had practically experienced it at first hand. Undoubtedly, for cultural reasons abundantly explained throughout this thesis (see sections § 1.5, § 3.3, § 5.3, and § 6.3), this combination of SCM with BIM for achieving SC integration was mostly observed in the Netherlands. And to answer 'why the SC integration has then not happened yet', the explanation could be probably found in the work of Arantes, Ferreira, and Costa (2015), according to whom whereas "all internationalised contractors also have a SCM strategy in place (…) the level of awareness of construction SCM is low" and greatly depends on the size of the contractor's organisation. Therefore, the SCM visions have been more diffused across the larger players in the global construction market. This calls for a change in the BIM era, given that the AEC industry cannot afford the competition among 'BIM-savvy' and 'BIM-illiterate' supply chains, which would then lead to even greater fragmentation.

After all, Mentzer et al. (2001) underlined that SCM could only take place after the alignment of a set of firms that display SC orientation, i.e. recognise the complications of the upstream and downstream flows, and thus the orientation of just one firm is not enough. Therefore, the existence of contractual means and "SC partnership (…) can be an important aspect of successful SCM" (Lambert et al., 2004). But as in practice, often SCM is only an 'orientation', it remains then a buzzword that could encourage the opportunistic behaviour. Thus, the SC contracts or framework agreements should continue being considered a prerequisite of SCM, as for many years a contractual relation entailed the absence of opportunistic behaviour (Williamson, 1985, pp. 42, 65). As in the construction industry "integrated approaches to information management (…) which are regarded as cornerstones of supply chain integration (…) in manufacturing" are not very popular (Vrijhoef, 2011, p. 233), the AEC is quite low in technology take-off. Therefore, the alignment of SCM and BIM – or in general of partnering and construction IT – requires at least some sort of relational-oriented partnership (see Chapter 5), and subsequently a fusion of collaboration, clear joint scope, ubiquitous 'BIM-learning', and use of construction IT.

§ 8.1.3 Scientific contribution

The most obvious contribution of this dissertation is made on the research approach and methodology, as it has approached both concepts of SCM and BIM from a systems' perspective. Thus, the research avoided the focus on 'dyadic relations' or 'focal' firms, and instead focused on the SC as a system (Christopher, 1992) that could be accurately represented as a network. For example, in a previous dissertation on SCM, Vrijhoef (2011, p. 113) analysed five cases of isolated focal firms, e.g. contractors or designers. Instead, in this thesis the contractors, designers, engineers, and suppliers were actors inside specific synergising multi-actor networks and not isolated players in the construction industry. The same contribution was made in the area of research and theory on BIM. Whereas, it has been previously acknowledged that the advancements pertinent to BIM affect the whole set of AEC stakeholders (Eastman et al., 2008), many recent BIM-related studies still focus exclusively on the designers (Ding et al., 2015; Son et al., 2015a), owners (Love et al., 2014; Korpela et al., 2015; Giel & Issa, 2016) or contractors (Ahn et al., 2015), neglecting other key actors of the AEC industry, such as the sub-contractors and suppliers, and likewise their interactions within a synergising multi-actor construction network. At the same time, this thesis aligns with the recent literature on BIM, according to which collaboration and the actor's soft competencies are an imperative for working with BIM (Davies et al.2015; Čuš Babič & Rebolj, 2016; Liu et al., 2016).

The most apparent theoretical contribution of this thesis is to SC thinking. Looking back to the literature on SC partnerships, this thesis has taken a more comprehensive standpoint. Even though partnering and alliances refer to both contractual and informal issues (Chao-Duivis, 1999), most of the state-of-the-art literature on SCM and SC partnerships focuses solely on the contractual and transactional aspects (Green et al., 2005; Fernie & Tennant, 2013) (see again section § 2.3). On the contrary, this thesis has focused on both the contractual and informal aspects (see Chapter 5) and attempted to have a balanced coverage of both transactional and relational BIM-enabled partnerships (see section § 5.5). After all, the view on SC thinking through this thesis is inter-organisational and focused on information as a means for optimising and support the other various SC flows, such as material and cash flows. This difference in the existing literature and this thesis is also underpinned by the analysis of studies in construction SCs from a M&S perspective (see section § 4.2), where the inter-organisational perspective was largely neglected. At the same time, recent research that reports that SCM is still a valid concept for the construction industry focuses more on the transactions and relations between the contractors and suppliers (Arantes et al., 2015), neglecting other actors in the SC. However, this thesis, as presented in the development of the analysis tool (see section § 4.4) and its partial implementation afterwards (see sections § 5.3 and § 5.4), focused not only on the dyad of contractor and supplier but also on the actors at the front part of the chain with a particular focus on investigating the 'split' between design and construction. Therefore, it can be concluded that SCM entails multi-faceted aspects which in turn might need a multi-disciplinary research approach, while the existing SC research is mono-disciplinary. Potentially, similarly to the way that this thesis departed from the literature on SCM, it could be a good idea to critically view BIM from an inter-organisational perspective, which is also in shortage (see section § 5.2), and avoid the mono-disciplinary and exclusive perspectives.

Looking at the problem space from a system's perspective, Dubois and Gadde (2002a) discussed that the construction industry is in principle a 'loosely coupled system' comprised of numerous various, rarely actually collaborating and usually competing, companies. In the context of collaborative design, Kvan (2000) also highlighted that it is essentially a 'loosely coupled system,' which could be better called 'compromised design' as it is a quite time-consuming task that necessitates relation management among the various actors. This dissertation has aligned these two 'loosely coupled systems' without compromising the complexity of neither the research problem nor of the suggested solution. Therefore, instead of vaguely simplifying the solution, it added new parameters and insights into the discussion of how to align Partnering with Construction IT to achieve SC integration in AEC. Therefore, during the 'modelling' of the solution to the problem, the complex system of the AEC industry was not simply reduced to the Process/Product/Actor framework produced in Chapter 2, but instead was enlarged to include as many possibly germane parameters that could lead to the solution (see Table 38 and Table 39). After all, Ackoff and Gharajedaghi (2003) have previously highlighted that "as social systems become increasingly more complex, simpler mental models of them do not reflect their emerging properties."

To avoid simplification and to capture as many as possible aspects of the concepts of SCM and BIM, the research attempted to map key concepts pertinent to SCM and BIM. These concepts are derived from the literature review (see Chapter 2), the empirical case data (see the quotations from sections § 3.4, § 5.4, and § 6.4), and the validation sessions (see again Table 28 and sections § 7.5 and § 7.6) to the intersection of SCM and BIM (see again Figure 1). Figure 35 compiles and maps these concepts – that according to this thesis – are pertinent to the intersection of SCM and BIM constructs. Some of the concepts are relevant to the intersection of SCM and BIM, e.g. the concepts in the centre of Figure 35, and some other concepts are found at the periphery of the intersection of SCM and BIM. For example, the concepts of 'co-locations', 'BIM scope', and 'trust' were deemed from the empirical case analyses and the validation sessions as crucial for the further integration of BIM-enabled SC partnerships, and therefore are placed in the central part of Figure 35 in the intersection of the SCM and BIM concepts. At the same time, the concept of 'BIM/FM' has been primarily linked to BIM-related debates and not yet associated with SCM-related research. Likewise, the 'logistics' concept has not yet been diffused in the BIM-enabled SC partnerships. Thus, these last two concepts are found at the periphery of the intersection scheme. Accordingly, as part of the thesis' theoretical contribution, Figure 35 presents some expectations about future trends and associations in the area of the combination of BIM and SCM research.

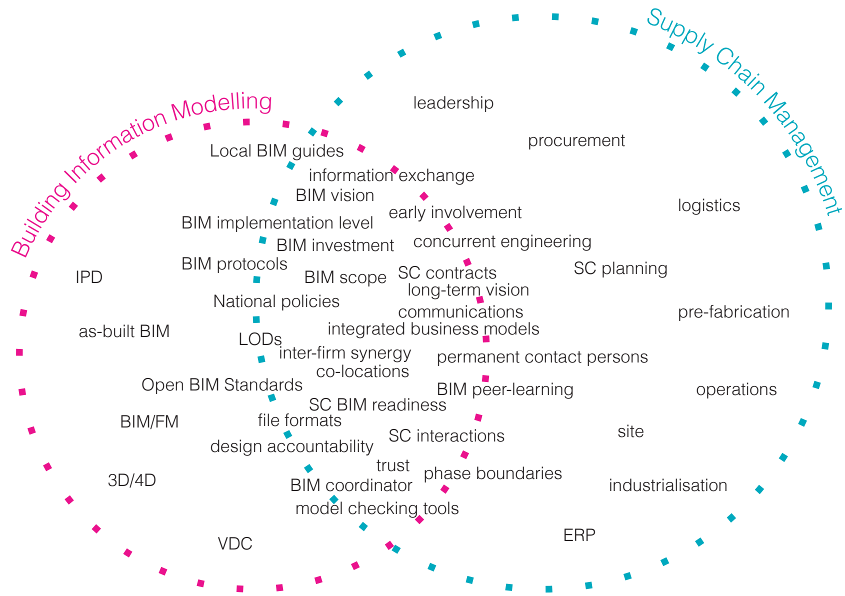

FIGURE 35 Concepts related to the intersection of the BIM and SCM, and concepts at the periphery of the thesis.

Another contribution of this thesis has taken place in the area of theory generation. As there has been little prior research on the topic of 'SC integration with BIM' and in particular only regarding SCM and integration (Vrijhoef, 2011), and no research on how to achieve integration from strategically deploying construction IT – e.g. BIM – the newly developed theoretical synthesis could be described as 'nascent theory'. Edmondson and McManus (2007) stated that 'nascent theory' generation aims more at understanding, avoids hypotheses, and usually involves exploratory data collection from organisational informants via interviews and observations. This type of theory generation is likely to focus on the research of organisational transitions, and could contribute to knowledge by either generating new constructs or presenting a 'suggestive model' to describe managerial processes (Edmondson & McManus, 2007). The latter is the case in this research, as this thesis has essentially focused on innovation change management, that is to propose strategies for integrated BIM-enabled partnerships. Accordingly, the main contribution has been this new theoretical correlation, and in particular alignment, between the concepts of SCM and BIM, as well as an operational framework (model) for how to achieve SC integration from their alignment (see Table 38 and Table 39).

§ 8.1.4 Limitations

Research limitations

First and foremost, a research limitation of the thesis was the focus on both concepts of BIM and SCM, which were prescribed in the PhD job description (see section § 1.1), and were treated equally throughout the research as 'independent variables'. This dual focus often kindled discussions about 'breadth' over 'depth' of the research. At the same time, according to Edmondson and McManus (2007) the resulted 'nascent theory' generation of concepts with little prior research, carries implicit limitations, given that the "research falls too far outside guidelines for statistical inference to convince other of its merits". In this research, the approach was largely explorative and empirical. However, all suggestions about "careful justification of theory building, theoretical sampling of cases, interviews that limit informant bias, rich presentation of evidence in tables and appendixes, and clear statement of theoretical arguments" made by Eisenhardt and Graebner (2007) were explicitly followed as previously presented during the Chapters 3, 5, and 6, and particularly in the 'methodology' sections § 3.3, § 5.3, and § 6.3. The theory generation process, that is the theoretical synthesis, was also explicitly documented in sections § 7.2 and § 7.3.

Apart from the research objectives, some limitations of this thesis could be found in the case selection. As the research problem of this thesis was located at the inherent complexities of the construction industry, a comprehensive exploration of the respective industry, i.e. Dutch construction market, had to take place. However, due to the lack of well-established pre-existing connections to the industry, and the lack of an industry-based 'problem-owner', the recruitment of the final sample of five case studies lasted around nine months in total and the study of the five cases studies for the empirical explorations of Chapter 3 started two years and three months after the official commencement of the PhD research in November 2012. Additionally, given that the two *polar* cases, which presented the most sophisticated BIM collaboration patterns, lasted more than 18 months, there was limited time for data collection and analysis, before the expiration of the doctoral employment contract. In particular, the research did not fully deploy all the features of the analysis tool developed in Chapter 4, because it would have required a largely extended data collection period. Given that various companies were involved in each case, it was challenging to align their timelines, so as to collect the data in a consistent manner and in the same format, although the modelling analysis tool was already in place and operational. However, the modelling decisions that underlined the tool were applied in Chapter 5, as the model was flexible and extendable. Therefore, the study remained mainly interpretative, and this limitation might fail to convince of its generalisation. However, in future studies, the tool and the underlying model could be applied to more cases.

To rectify the afore-described limitations regarding the scope, methodology, and research design, as well as gain additional insights into the research, three consecutive validation steps were undertaken. The three validation steps, regarding 'construct', 'internal', and 'external' validity, attempted to discuss, test, and evaluate the research parallel to its completion (see Chapter 7). As explained in the introductory chapter (see section § 1.4), because of the fact that this research fell between the areas of Engineering and Social and Management Science, inter-disciplinary input was used, e.g. from Systems Theory, Modelling, and Organisational theory. This inter-disciplinary character of this dissertation might be explained again in the context of 'nascent theory' generation from Edmondson and McManus (2007), given that it is a prerequisite for the generation of this type of theory.

Practical limitations

One of the practical limitations, that emerged from the discussions with the experts, who were mainly industrial practitioners, was the lack of insights into the outcomes of the projects and the impact of combining SCM philosophy with BIM technology (see section § 7.6). Whereas this did not take place due to the time constraints relevant to the projects' duration discussed above; the 'internal validity' sessions attempted to validate the intermediate research findings. Moreover, another limitation was that to study SC partnerships and the effects of SCM; probably longitudinal studies are in general more relevant. For example, a duration of eight years intervened between the theoretical model proposition of Lambert et al. (1996) and its validation (Lambert et al., 2004). Another example is the work of Gosling et al. (2015) who provided evidence on the interaction effects of various decisions for SCM, by following the study objects in a longitudinal study of twenty years. However, attempting a longitudinal study would probably not be suitable, as the 'BIM' parameter constantly changes and the developments in construction IT occur at a faster rate than those around the area of SCM. Instead, this study followed the approach of Eriksson (2015) who focused on project-based chains and not on multiple projects from the same chain.

Regional and cultural limitations

Because both integrated approaches to the building industry and BIM adoption have been quite prominent in the Netherlands; this country was the common ground for their further investigation. After all, this is why this PhD position was probably created in the first place. Whereas the regional and cultural setting could be considered a research limitation, it could be probably used as a basis for generalisation, after acknowledging its cultural and contextual boundaries. The firms of Dutch AEC are quite proactive as to technology adoption and consensus-seeking. Winch (2002, p.

25) described the Dutch construction industry as a *Corporatist type System* according to which, the 'social actors' are more keen to negotiate and coordinate to control the market. Dorée (2004) claimed that "*efforts to reduce risks and uncertainties are engrained in Dutch culture*." This corporatism has had a significant role in reducing costs and risks for various AEC stakeholders (Bremer & Kok, 2000). To define how representative is the Dutch construction industry to the rest of the construction markets, the UK market, from where most relevant cited scientific literature, best practices, and standards originated, could act as a comparator. The UK is not used to represent dogma or expertise, but rather simply to facilitate the comparison to another Western-European country.

Both the Dutch and the UK construction industries are equally fragmented or problematic. For example, in the Netherlands, the construction industry is highly fragmented and diversified (Bemelmans et al., 2011), with about 80% of firms being small enterprises with one or two employees (Rijt et al., 2010). Moreover, the Dutch construction firms are rather dominantly present among the largest European construction companies (Rijt et al., 2010). In the Netherlands, the developments of Research and Development (R&D) activities are again an outcome of a mixture of the high level of corporatism and state involvement when introducing innovations (Bremer & Kok, 2000). Potentially any lessons learned from the Netherlands, which is a smaller and more reactive construction market (Abbott, Vrijhoef, & de Ridder, 2006), might accordingly reflect future trends in the UK and other larger countries' construction markets. The ambient collaborative culture of the Netherlands, however, cannot be directly transferred to another country via R&D investment and thus, it remains the greatest cultural limitation of the study.

§ 8.2 Conclusions

§ 8.2.1 Revisiting the Research Questions

This research was structured around six key research questions that focused first on describing the research problem (*description* part), second analysing the problem based on multivariate aspects (*analysis* part) and, third synthesising a solution (*synthesis* part). The key research questions will be next revisited and answered; afterwards, they will amount to answering the main research question of the thesis.

RQ#1: What design and construction challenges of the AEC industry could the SCM and BIM concepts potentially manage? (Chapter 2)

TOC

Various design and construction challenges currently dominate in the AEC. These challenges pertain to either the inherent complexities of the industry or its emerging fragmentation and disintegration that has taken place the years that followed the introduction of project management principles in AEC. On the one hand, historically the concept of SCM was deemed appropriate for managing the processual challenges of AEC industry. Nowadays the concept of SCM also pertains to a more pragmatic, actor-related perspective and could subsequently manage the actor-related – or organisational – challenges emerging in construction networks. In practice, the concept of SCM usually manifests as strategic partnerships, or SC partnerships, as a structure for managing the processual and organisational complexities.

On the other hand, BIM is a set of technologies, tools, and means for managing the technical - or product-related – complexities of AEC, as it has emerged from Building Product Models. As the various built-in features of BIM and the current research directions relate to the work of various multi-disciplinary actors of the AEC industry, BIM slowly acquires an organisational perspective as well. BIM could manage apart from the technical, also the organisational complexities of AEC, and particularly those pertaining to communication, collaboration, and coordination of work. *Therefore, the two concepts combined – SCM and BIM – could in turn together manage the processual, product-related, and actor-related or organisational (P/P/A) complexities of Design and Construction Management* (answer to RQ#1).

RQ#2: What are the interdependences between BIM technology and SCM practices in real-world settings? (Chapter 3)

Having established the conceptual link between BIM and SCM concepts, a practical link was sought. The empirical analysis of five real-world cases of simultaneous BIM and SCM deployment provided evidence on the interplay between BIM implementation and SC partnering relations, and particularly on the collaboration process. Accordingly, some BIM collaboration patterns emerged from these observations. The BIM-enabled SC partnerships – and probably other remotely inter-organisational settings – display three BIM-based collaboration patterns with the following characteristics:

- *ad-hoc* pattern which features on-demand meetings, firm-based BIM protocols, exchange of 2D drawings, native files;
- *linear* pattern which features selection of BIM-savvy partners, on-demand meetings and co-locations, both firm-based and joint BIM protocols, exchange of 2D drawings and both proprietary and open files;
- *distributed* pattern which features BIM-related contractual requirements, selection of BIM-savvy partners, pre-scheduled meetings and co-locations, joint BIM protocols, exchange of both proprietary and open files.

The parameters of these patterns are processual, product-related, and organisational, following the P/P/A framework developed in Chapter 2. *The concepts of BIM and SCM are highly interdependent regarding the (a) organisational parameter, e.g. the combination of contractual means and partner selection criteria, (b) processual parameter, e.g. the deployment of physical interactions, such as pull-planning sessions and BIM-related co-locations, and (c) product-related parameter, e.g. the use of SC framework agreements, quasi-contractual BIM specification protocols, model checking tools, and standardised information exchange formats* (answer to RQ#2).

RQ#3: How to combine the SCM with BIM concepts to analyse BIM-enabled SC partnerships? (Chapter 4)

The afore-described emerging BIM collaboration patterns further underlined the complexity of the collaboration among BIM-enabled SC partnerships and stressed the need to investigate the SC coordination mechanisms additionally. As BIM is an aspiring integrator of information flows for SCM in AEC, a modelling methodology is introduced to analyse the complex AEC SC system and offer insights into the SC coordination mechanisms of BIM-enabled SC partnerships. *After combining organisational models derived from SCM philosophy and building information from BIM, the developed graph-based model for the analysis of BIM-enabled SC partnerships offers a pragmatic approach to making sense of the coordination process, understand the manifestations of the notions of order and control, and potentially later contribute to the management of the organisational, processual, and product-related complexities in AEC* (answer to RQ#3). Developing this analysis model in an E-R fashion made it extendable, so that more parameters could be added in the future, and holding a network perspective throughout the concept brought its applicability closer to reality.

The SC coordination mechanisms are explored through the developed SC analysis tool, based on the combination of product models with processual and organisational information in a structured graph-based representation of the AEC SC partnerships. Besides illustrating the processual, product-related, and organisational complexities of AEC, the proposed model produced dynamic analyses of the processual and organisational aspects in a real-world case study, as a proof-of-concept. The findings from the case identified an imbalance in the relation between the project phasing and the interactions of actors, either internal to the SC partnership, i.e. strategic, or external. The findings of the scenario case suggest that to analyse coordination in BIM-enabled SC partnerships, not only the analysis of the information flows, but also the analysis of the processual attributes, and the inter-organisational relations are indispensable. From such analyses, inferences for improving the BIM-enabled SC partnerships could be drawn.

RQ#4: What are the effects of BIM-enabled SC partnering on the formal and informal relations of the Supply Chain? (Chapter 5)

The afore-described analysis tool for the exploration of SC coordination mechanisms was combined with exploratory and qualitative analyses of the two real-world polar cases of BIM-enabled SC partnerships. Accordingly, it was deemed germane to investigate the formal and informal inter-organisational relations of the BIM-enabled SC partnering. The two studied construction networks displayed asymmetrical and formal in Case A, emphasising the transactions, whereas in Case B they were asymmetrical and informal, emphasising the relations. *The effects of BIM-enabled SC partnering on the inter-organisational relations, such as the SC contracts and the selection of BIM-competent partners is that the formal relations are not solely sufficient to instigate informal relations among the actors, such as proactive communications, commitment to scope, trust, and support the SC partnerships* (answer to RQ#4).

The integration of the BIM-enabled SC partnerships additionally depends on whether the partnership is transactional or relational, i.e. the shared partnering goals of the SC partnership. Their integration also depends on the composition of the strategic or internal partnership, whether it was more supplier- or engineering-oriented, and particularly on the participation or not of the architect and the client. Overall, the sophisticated BIM collaboration pattern presented in Chapter 3, i.e. '*distributed*' pattern, requires additional informal aspects of communication, such as the interest towards seeking consensus, accepting joint responsibility, inclination for shared learning, and encouragement of early involvement, and communication across multiple tiers. To this end, a combination of BIM competency and keenness to diffuse BIM knowledge and experience across the SC partnership promotes further SC integration during design and construction phases.

RQ#5: How does BIM impact the intra- and inter-organisational relations of BIM-enabled SC partnerships? (Chapter 6)

The interplay between SC partnering and BIM pertains not only to inter-organisational but also to intra-organisational aspects. The set of the two polar cases of BIM-enabled SC partnerships, which were studied regarding the formal and informal relations in Chapter 5, were further analysed to reveal additional compatibilities and incompatibilities of the BIM and SCM constructs. The analysis highlights the paradox of *SC Planning* being considered either the result of *Joint SC Operations* (case A, operational) or of a pre-agreed shared SC *Scope* (case B, strategic) from the two polar cases, and thus, its association with different hierarchical levels in each case. Another inter-organisational paradox is considering *Communications* as the result of either pre-existing *Trust* (case B), or of intensive project-based *Joint Operations* (case A). *Subsequently, it is concluded that the concepts of SCM and BIM and their deployment from SC partnerships depend primarily on the pre-existing history and cultural alignment – at an operational level –, rather than the contractual agreements – at a strategic level* (answer to RQ#5). To further strengthen the BIM-enabled SC partnerships, explicit shared SC scope, and BIM-related agreements are preeminent.

Whereas the research focus is the AEC firm, additional intra-organisational insights into the firms of engineers, contractors and suppliers were obtained, and particularly as to the alignment of their business models to BIM-enabled SC partnerships. *Several aspects at the periphery of the research objectives are essential for instigating further integration of the BIM-enabled SC partnerships* (answer to RQ#5):

- Motives for BIM & SCM adoption: whether it is external or internal for each involved SC firm;
- Synergy among intra-firm hierarchy: whether the firms are of rigid or horizontal hierarchy;
- BIM & SCM vision into firms' business plan: whether it is opportunistic or incorporated;
- Intra-firm BIM-related functions: whether there are multiple or all-around BIM functions;
- Services offered per firm: whether the firms offer specialised or integrated services;
- BIM implementation by the firm: whether the BIM is out-sourced or generated in-house

The above intra-organisational aspects relate to various hierarchical levels, from top management to work floor. Further aligning the intra-organisational business models to the scope and vision of the BIM-enabled SC partnerships is essential for inducing SC integration.

RQ#6: How could the BIM-enabled SC partnerships be shaped after the alignment of SCM philosophy with BIM technology? (Chapter 7)

From the findings derived from the empirical data, it could be concluded that there are two main routes for achieving SC integration. The two polar cases of BIM-enabled SC partnerships followed a 'product-related' route and an 'actor-related' route to integration respectively. From the combination of the observed approaches and activities in the polar cases, two sets of network strategies for SC integration were extracted, revisited, and improved after the external validation of section § 7.6. These strategies – or 'courses of action' – are presented in Table 40 and Table 41 (answer to RQ#6). The strategies do not differentiate as to the processual, product-related, and organisational dimensions of the P/P/A framework from Chapter 2. Given that the strategies pertain to various intra-organisational aspects, they are categorised into the three hierarchical levels, i.e. strategic, tactical, and operational, to facilitate their adoption from SC partnerships or other inter-organisational networks. Table 40 and Table 41 also include the outcome of the external validation session (section § 7.6) to indicate to what extent the proposed strategies were approved by the group of experts. As some strategies were extensively discussed and other were at the periphery of the validation discussions (see Table 37), the outcome indicates whether the strategies were discussed as well as a description of their conditional applicability where appropriate.

TABLE 40 Strategies for SC integration via the 'actor-related' route, including the results of the validation.

LEVEL	'ACTOR-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUTCOME
Strategic	1. Issuing explicit formal SC framework agreements with elements of BIM protocols;	Yes*
	2. Partnering with firms with integrated business models, e.g. MEP firms;	Con*: large projects
	3. Top management support for SCM adoption and inter-organisational synergy;	Con: engagement
	4. Adjustment of the BIM scope and planning to the SC's scope and commercial decisions.	Con: project manager
Tactical	5. Establishment of permanent contact persons across the SC partnership;	Inc*
	6. Early involvement of the suppliers in the Design and Engineering phases;	Con: trust
	7. Pre-scheduling frequent and time-wisely strategical co-locations for BIM collaboration;	Yes
Operational	8. Sharing a collective future vision for both BIM and SCM at a work floor level;	Con: clear BIM scope
	9. Encouragement of informal communication across multiple tiers;	Yes
	10. Balance between internal and external SC actors and reciprocal interactions;	Con: co-locations
	11. SC partnership's flexibility and adaptability to obscure phase boundaries;	Inc
	12. Increase of intra- and inter-firm communications to increase commitment and trust;	Yes
	13. Digital information exchange of IFCs and proactive informal ad-hoc communications.	Con: trust

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

TABLE 41 Strategies for SC integration via the 'product-related' route, including the results of the validation.

LEVEL	'PRODUCT-RELATED' ROUTE TO SC INTEGRATION	VALIDATION OUTCOME
Strategic	1. Selection of BIM-savvy partners and in-house BIM investment, instead of outsourcing;	Inc*
	2. Alignment of the firms' BIM readiness with the SC partnership's BIM maturity level;	Yes*
	3. Partnering across firms with compatible BIM (internal/external drive) and SCM visions;	Inc
	4. Joint SC agreements about the BIM protocols and clear project/SC BIM scope;	Con*: BIM manager
	5. Alignment of the BIM models with local BIM specifications and National BIM policies.	Yes
Tactical	6. Joint agreements on the BIM LODs and clear design accountability;	Con: trust
	7. Clear role of BIM coordinator and choice between the proprietary or open deliverables;	Yes
	8. Inter-firm BIM peer-learning and training;	Con: clear BIM scope
	9. Elimination of the gap between strategic and operational planning at SC and firm levels.	Con: project manager
Operational	10. Prioritisation among ad-hoc, linear, and distributed BIM collaboration patterns;	Yes
	11. Information exchange of IFCs and provision of stable physical and digital infrastructure.	Con: clear BIM scope

*Legend: 'Yes': Discussed and approved strategy, 'Inc': Inconclusively discussed strategy, 'Con': Condition(s) of applicability

§ 8.2.2 Overall Conclusions

After responding to the key research questions, the main research question could be then answered based on the previous statements, derived from Chapters 2 to 7, and the answers provided above. The main research question was:

How to align the SCM philosophy with BIM technologies to achieve integration in the construction industry? What aspects contribute to this alignment?

From the empirical findings, it could be concluded that there are two main routes to achieving SC integration from the alignment between SCM philosophy and BIM technologies: a 'product-related' route and an 'actor-related' route. As these two routes emerged from the two polar cases, it is advisable for construction managers that their respective strategies (see Table 40 and Table 41) not to be deployed in isolation, but rather as complementary strategies and routes instead. The two routes could facilitate the identification of which approach is the 'closest fit' to SC integration, and then support the decision-making process about which route to follow. Afterwards, the proposed model from Table 40 and Table 41 could be used primarily as a diagnostic 'checklist' tool, and in turn to advise on the deployment of specific strategies to integrate new or existing BIM-enabled SC partnerships.

Apart from identifying the two routes to integration, the preferred theory will be presented, after the discussions that took place with the external experts in sub-section § 7.6.4. Based on the two routes to integration presented in Figure 30 in section § 7.3, "Synthesis of a model for BIM-enabled SC partnerships", different projections could be made. Given that the concept of BIM is currently a hot topic in the industry, it might be wise to undertake a 'product-related' route to integration and gradually introduce strategies from the 'actor-related' route to integration. However, the 'actor-related' route might lead to more long-term benefits for SC integration and subsequently highly consistent relations among the multi-actor construction network. Simultaneously, the long-term trusting relations among the various actors could accordingly prepare the ground for innovation change management and smoother acceptance and adoption of future construction IT developments. As the underlying technologies that fall under the umbrella of BIM could soon transform – by being either heavily or slightly renamed – or significantly updated, a generic change management approach is probably more relevant. Therefore, the 'product-related' route could be represented as a steep logarithmic curve, whereas the 'actor-related' route to SC integration as an exponential curve. Figure 36 illustrates the two routes to integration, under the above hypotheses, as well as the locations of the two cases, where the empirical data for the synthesis of the theory were drawn from.

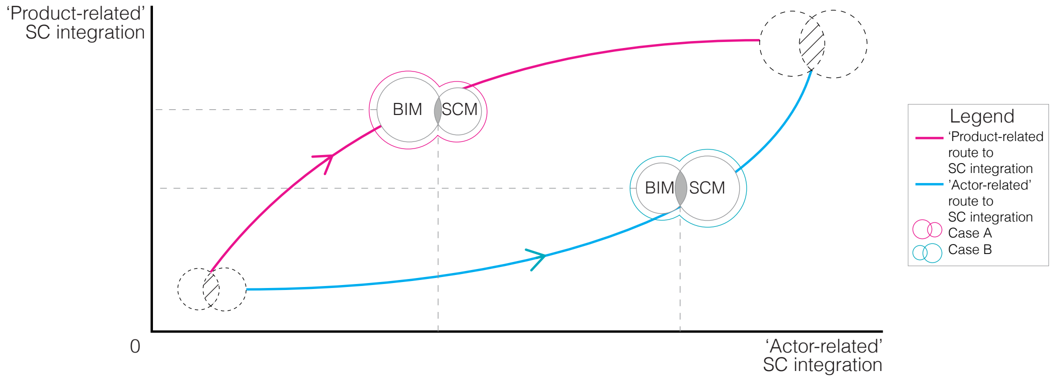

FIGURE 36 The two routes to achieve SC integration and the degree of integration in Cases A and B.

Finally, after presenting the route to SC integration based on the alignment of SCM and BIM, it could be concluded that the key aspects of this alignment for long-standing, young, or future BIM-enabled SC partnerships are:

- The type of the complexity in the BIM-enabled SC partnership, e.g. whether it is of processual, product-related, or organisational nature (Chapter 2);
- The deployed BIM collaboration patterns, i.e. *ad-hoc*, *linea*r or *distributed* (Chapter 3);
- The SC coordination mechanisms, e.g. centralised or decentralised (Chapter 4);
- The relation between formal and informal aspects, e.g. symmetric or asymmetric (Chapter 5);
- The emerging inter- organisational and intra-organisational relations (Chapter 6);
- The various inter- organisational and intra-organisational hierarchical levels of decision-making that BIM-enabled SC partnership pertains (Chapter 7).

From the above, it is concluded that the alignment of partnering with construction IT is a complex task for innovation change management that entails the introduction of new multi-faceted considerations, both organisational and technical, to the toolbox of construction managers and researchers.

§ 8.3 Outlook

§ 8.3.1 Applications in industry

The theoretical synthesis and the proposed operational framework of strategies for the integration of BIM-enabled SC partnerships, could provide concrete directions and application areas for the industry. In this spirit, the research products were tailored for the construction managers and any other kind of managerial or high-level decision-makers across the AEC firms. The difference from other approaches is the holistic consideration of various parameters not associated before, that is the alignment among process, products, and actors. The above would probably mean for the industry that the managerial emphasis for managing complexity in AEC would have to shift towards more organisational aspects, and not only focus on processual controls, such as time- and budget-keeping. Likewise, what this thesis brings afresh to the industry is the need to collaborate across the various hierarchical intra-organisational levels and beyond the organisational boundaries. Simultaneously, it is germane to realise that the adoption and diffusion of construction IT, does not strictly derive from following the National – or whatsoever European – policies. Instead, as some standards have emerged from the close cooperation among industrial consortia and most of the construction IT developments take place at a 'bottom-up' level, embracing this 'cooperative culture' would be a meaningful way forward for SC integration in AEC. After all, simply hinging the integration on Information Systems' interoperability is not sustainable, in the long run, and it has to be complemented by inter-organisational initiatives as well.

§ 8.3.2 Applications in education

This thesis has underlined the problem that the AEC industry has been quite under-developed in the adoption of IT, as opposed to other industries. The reluctance for the adoption of digital technologies might stem from the domain of Architecture, which essentially oscillates between being a 'creative industry' or an engineering discipline – or both. The transition from the 'analogue' to the 'digital' has been debated for decades in Architectural Schools around the world. The adoption of construction IT and in particular BIM, which is currently a fad for AEC, presents implications not only for accepting and incorporating the digital technologies in the architectural and engineering curricula but also for how to best do so. In essence, the most hesitant approaches have tried to add BIM as a special course. Also, BIM-specific MSc programmes have emerged. These two approaches will likely increase the fragmentation in AEC as they would create new 'experts' or 'specialists', attached to a particular type of construction IT, who would be probably inflexible to migrate to a new technology in due time. This observation resonates with the constant transitions in other industries, such as the Software Engineering industry, where the practitioners are constantly faced with the dilemmas about adjusting to new developments in programming languages or continuing to use – soon to be – obsolete technologies.

Instead, the novices of the AEC industry should learn how to use BIM software – and the associated technologies that fall under the umbrella of the term 'BIM' – and any other construction IT to enrich their process and achieve the respective – design, engineering, or managerial – benefits. It would be then necessary to incorporate BIM into existing educational curricula, such as e.g. construction management, quantity surveying courses, design coordination, design, and engineering. Moreover, this dissertation has something to recommend concerning multi-disciplinary education in AEC. Similarly to practice in general, in education too, BIM has come to teach the industry not only about digital technologies but also about collaboration and coordination. The alignment of the construction IT with SCM philosophy and partnering is topical to prepare the future AEC professionals for multi-disciplinary collaboration and a better understanding of the building feasibility and constructability. Because of the enhanced transparency in the process that BIM offers, the various actors could gain increased understanding and insights into the work of the other disciplines, and potentially become more condescending and not antagonising. Based on the above, multi-disciplinary courses and role-playing BIM-assignments could strengthen the perception of the students about the Built Environment and prepare them for this – undoubtedly – fragmented, yet fascinating industry.

§ 8.3.3 Future research

This thesis on the alignment of Partnering to Construction IT has had previously implied some directions for further research, in the 'construct', 'internal' and 'external' validation sessions (see sections § 7.4, § 7.5, and § 7.6) as well as during the research limitations of this chapter, (see section § 8.1). First, and in increasing order of importance, future research could focus on the proposed strategies of the theoretical synthesis and further operationalise them with the aim to explore them in other empirical settings. Since the developed theory was largely 'nascent theory', additional empirical explorations might increase the research value. It would also be worthy to investigate to what extent these findings resonate with other cultural settings, given that the construction industry also enters an era of globalisation, and the large contractor firms now compete at a global level, and could, thus, potentially transfer cultural and organisational idiosyncrasies beyond national borders. Therefore, deploying the methodologies of this research to additional real-world cases would provide a grounded understanding of the ramifications in BIM-enabled SC partnerships and potentially new insights into the alignment of Partnering with Construction IT. Second, it could probably be germane to continue the exploration of the two *polar* cases in a longitudinal study, with the aim to observe the changing relationships among the contractors, engineers, and suppliers beyond project-based focus.

Third, future research could focus on the methodology, and in particular in further developing the proposed analysis tool of Chapter 4 with the aim to gain additional insights into the coordination mechanisms and the subsequent causalities that could induce SC integration from the alignment of SCM philosophy with BIM. Focusing on the further development of the proposed analysis methods from Chapter 4 could have a two-fold advantage: (a) first it could counterbalance any methodological limitations, pertinent to 'nascent theory' generation, and (b) offer more insights into the project outcomes, as an I/O method. A deeper investigation into the already operationalised parameters of the developed model, as well as into the emerging parameters from the empirical studies of Chapters 5 and 6, could shed more light on the impact of BIM and SCM on managing the complexities of the AEC industry. As the proposed analysis tool of Chapter 4 has been modelled with principles of E-R models (see § 4.6), it is extendable and could include additional inter-organisational relations, such as power, trust, knowledge transfer, among others. After all, from both the case narratives in Chapter 6 and the experts' feedback 'process re-design' is an imperative, and that could only be achieved through meticulous analysis, coordination, and management of the process. As this research has approached the AEC industry from a systems' perspective – and particularly from a network and not a hierarchical angle –, future research could continue viewing integration as the potential end goal of close multi-disciplinary collaboration, coordination, and inter-organisational synergy. Aligning Partnering and SCM philosophy with Construction IT, and particularly BIM, is not a goal per se, but rather a step towards the long-standing effort to additionally align the 'supply' with the 'demand' side of the AEC industry through partnering and using construction IT across both sides of the supply chain.

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Appendix A

Intake interview

The questions of the intake interview about the eligibility of the projects for the case study were:

- What is your function and contact information?
- What is the basic information about the project (scale, type, m2)?
- Could you tell me something about the project (e.g. goals, challenges)?
- Which actors (SC partners) were involved in the partnership?
- Which of the following parameters are explicitly stated in your contract with your SC partners (time, price, quantity, quality, communication)?
- How was the SC partnership formed, and the partners selected/sourced?
- With which SC partners have you already been partners and for how many projects?
- To what extend is the SC partnership restricted geographically?
- What are the main project milestone dates?

Phase I

The questions for the interviews towards the internal SC partners about the strategy of the SC partnership were:

- Is the SC partnership strategically aligned for acquiring new projects (if yes, how)?
- Are the roles each SC partner planned (if yes, how)?
- Are the business plans of each SC partner coordinated (if yes, how)?
- Does the SC partnership integrates its operations, e.g. pull planning sessions, quality management, and performance metrics?
- How defined are the SC relationships with: the clients, the other partners and the workplace culture of your partners?
- What is the marketing approach of the SC partnership (common or separate)?
- How does the SC partnership manage information?
- Does the SC partnership shares a common approach to technology investment?

Phase II

The questions for the interviews towards the internal SC partners about BIM implementation were:

- How much experience (years) with BIM has this SC partnership?
- In which project stage is BIM mostly used?
- What is each partner's BIM readiness?
- Do you use a particular BIM protocol among the SC?
- What BIM software infrastructure is used?
- What BIM tools are used and for which project goal/phase?
- What BIM-based interoperability routine do you use among the SC partnership?
- What major issues have surfaced in your BIM-based interoperability routine?

Phase III

The questions for the interviews with the various actors about the performance of the project and the chain were:

- How could you describe your position/function in your company?
- Could you give me some background information about the project (e.g. goals, challenges, performance)?
- What was the motivation of your company on engaging to Supply Chain partnerships?
- What were the main activities that Supply Chain partnership/SCM was used for in the project and were there any benefits and challenges you have observed in relation to it?
- What was the motivation of your company on applying BIM?
- What were the main activities that BIM was used for in the project and were there any benefits and challenges you have observed in relation to it?
- Considering the above, how does your company plan to engage with this SC partnership in the future?

Appendix B

Data schema used as input for the model

TABLE 42 Type of information about the actors participating in the BIM-enabled SC partnership case.

COMPANY NAME	COMPANY	BIM USER	INTERNAL PARTNER	COMPANY SIZE	EMPLOYED PERSONS
Actor 1 (for anonymity)	Contractor	TRUE/FALSE	TRUE/FALSE	[Integer]	[Integer]
Actor 2	Supplier	TRUE/FALSE	TRUE/FALSE	[Integer]	[Integer]
Actor 3	Architect	TRUE/FALSE	TRUE/FALSE	[Integer]	[Integer]
...	...	...	...	...	...
Actor n	Supplier	TRUE/FALSE	TRUE/FALSE	[Integer]	[Integer]

TABLE 43 Type of information about the phases of the BIM-enabled SC partnership case.

PROCESS NAME	START DATE	END DATE	BIM USE
Phase 1	DD-MM-YYYY	DD-MM-YYYY	TRUE/FALSE
Phase 2	DD-MM-YYYY	DD-MM-YYYY	TRUE/FALSE
Phase 3	DD-MM-YYYY	DD-MM-YYYY	TRUE/FALSE
...	...	...	...
Phase n	DD-MM-YYYY	DD-MM-YYYY	TRUE/FALSE

TABLE 44 Type of information about the generated products (IFC translation) of the BIM-enabled SC partnership case.

PRODUCT NAME	COUNT	OBJECT TYPE	TIMESTAMP	CREATED BY
IfcEntity 1	[Integer]	[Integer]	YYYY-MM-DDTxx:xx:xx	Actor n
IfcEntity 2	[Integer]	[Integer]	YYYY-MM-DDTxx:xx:xx	Actor n
IfcEntity 3	[Integer]	[Integer]	YYYY-MM-DDTxx:xx:xx	Actor n
...	...	...	...	...
IfcEntity n	[Integer]	[Integer]	YYYY-MM-DDTxx:xx:xx	Actor n

Data schema tabulated in the Gephi environment

TABLE 45 Node page from Gephi's 'Data Laboratory'.

ID	LABEL	NODECOLOR	START DATE	END DATE	TIME INTERVAL
1	Actor 1	#454af8	DD-MM-YYYY	DD-MM-YYYY	<[(e notation number) (e notation number)]>
2	Actor 2	#454af8	DD-MM-YYYY	DD-MM-YYYY	<[(e notation number) (e notation number)]>
3	Phase 1	#45e595	DD-MM-YYYY	DD-MM-YYYY	<[(e notation number) (e notation number)]>
...	...	...	...	...	...
n	Product n	#FF0000	DD-MM-YYYY	DD-MM-YYYY	<[(e notation number) (e notation number)]>

TABLE 46 Edge page from Gephi's 'Data Laboratory'.

SOURCE	TARGET	TYPE	ID	LABEL	START DATE	END DATE	TIME INTERVAL
Actor 1	Phase 1	Directed	1	Initiator/Enabler/Executor	DD-MM-YYYY	DD-MM-YYYY	e*
Actor 2	Phase 2	Directed	2	Initiator/Enabler/Executor	DD-MM-YYYY	DD-MM-YYYY	e
Product 1	Phase 3	Directed	3	Input/Output	DD-MM-YYYY	DD-MM-YYYY	e
...	...	...	...	...	...	...	...
Product n	Phase n	Directed	n	Input/Output	DD-MM-YYYY	DD-MM-YYYY	e

*e: <[(e notation number) (e notation number)]>

Network view of the case from Gephi

The network visualisations of the proof-of-concept case have been produced with the use of the Gephi layout 'ForceAtlas2'. ForceAtlas2 is a force-directed visualisation layout for network spatialisation (source: github.com/gephi/gephi/wiki/Force-Atlas-2). For the ForceAtlas2 layout, gravity, i.e. the attraction to the centre, of size 0.1 has been used.

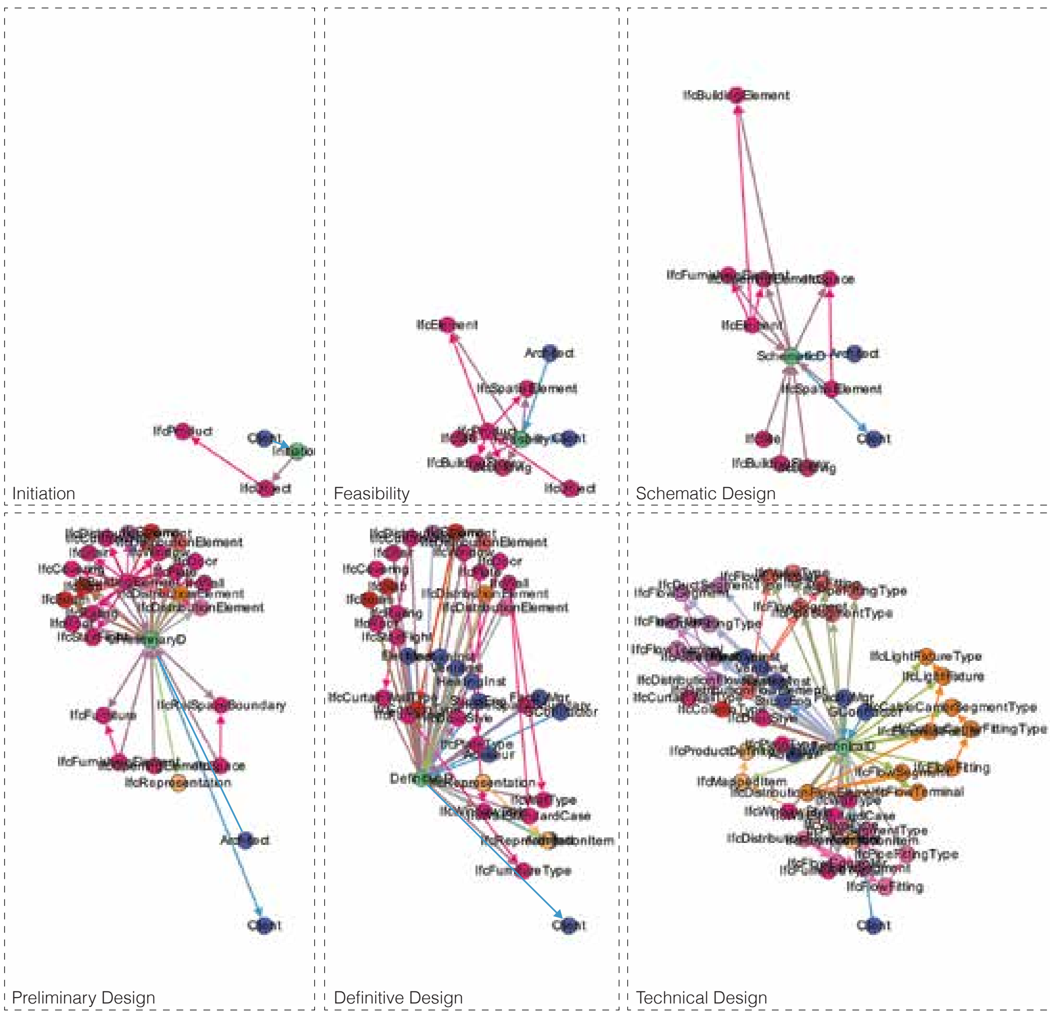

FIGURE 37 Snapshots of the model applied to the scenario case from Initiation to Technical Design phases.

TOC

Code from R for the analysis of the Gephi tables

The analysis of the 'node' and 'edge' tables (Table 45 and Table 46) was made by code written in R language. The code consisted of two scripts: (a) a 'node' script and (b) an 'edge' script. At the same time, a 'for-loop' repetition control structure code was written to execute parts of the previous scripts for a specific number of times.

Script for the analysis of the network's 'nodes':

```
setwd("~/Dropbox/PhD/R/Helling-R")

# File input (nodes):
gephinodes <- read.csv(file="Helling-20150330-Nodes.csv",sep=",",head=TRUE)
gephinodes
gephinodesdf <- as.data.frame(gephinodes)
typeof(gephinodesdf)

# General overview:
names(gephinodes)
plot(gephinodes$NodeColor, main='Supply Chain system nodes', xlab='Types of nodes',
col="lavender")

# Transform time units:
# gephinodesdf$Start <- strptime(gephinodesdf$Start,"%Y-%m-%d")
# gephinodesdf$End <- strptime(gephinodesdf$End,"%Y-%m-%d")

gephinodesdf$Start <- as.Date(gephinodesdf$Start)
gephinodesdf$End <- as.Date(gephinodesdf$End)

# Calculate durations:
numgephi <-NROW(gephinodesdf)
numgephi
diffgephi <- difftime(gephinodesdf$End[1:numgephi], gephinodesdf$Start[1:numgephi],
units="days")

# Transformation of the durations to integers:
durgephi <- as.data.frame(diffgephi)
durgephi2 <- as.integer(durgephi$diffgephi)
durgephi2

# Updated list:
newgephinodesdf <- cbind(gephinodesdf,durgephi2)
newgephinodesdf

# Rename the column name of the added list:
colnames(newgephinodesdf)[colnames(newgephinodesdf)=="durgephi2"] <- "Duration"
newgephinodesdf

# Sort the processes dataframe by time:
processesdf <- subset(newgephinodesdf, NodeColor=='Processes')
numproc <- NROW(processesdf)
processesdf
sortprocessesdf <- processesdf[order(processesdf$Start), c(1,2,3,4,5,6,7,8,9,10)]
```

```
sortprocessesdf

# Overview of actors' involvement:
productsdf <- subset(newgephinodesdf, NodeColor=='Products')
actorsdf <- subset(newgephinodesdf, NodeColor=='Actors')
sortactorsdf <- actorsdf[order(actorsdf$Duration), c(1,2,3,4,5,6,7,8,9,10)]
plot(sortactorsdf$Duration, type="o", pch=19, col="blue", main='Involvement of the SC
Members',
xlab='Stakeholders', ylab='Duration in days', axes=FALSE, frame.plot=TRUE)
Axis(side=2, labels=TRUE)
Actornames <- as.vector(sortactorsdf$Label)
Actornames
typeof(Actornames)
text(sortactorsdf$Duration, Actornames, cex=0.5, pos=3, offset=0.4, col="dimgray")

# Overview of the processes load:
plot(sortprocessesdf$Duration, main='Duration of the phases',
xlab='Phases', ylab='Duration in days', axes=FALSE, frame.plot=TRUE)
lines(sortprocessesdf$Duration, type="o")
Axis(side=2, labels=TRUE)
procnames <- as.vector(sortprocessesdf$Label)
procnames
text(sortprocessesdf$Duration, labels =procnames, cex=0.5, pos=1, col="blue")

#FOR LOOP
#seq(as.Date("1910/1/1"), as.Date("1999/1/1"))
setwd("~/Dropbox/PHD/R")
source("4Loop.R")
datesProcesses <- listOfDates (processesdf)
print(datesProcesses)
ActorsActiveInIntervals<- createTuples(datesProcesses,actorsdf,findUsers)
ProductsActiveInIntervals<- createTuples(datesProcesses,productsdf,findUsers)

# General overview of the actor entities per phase:
newsortprocessesdf <- cbind(sortprocessesdf,ActorsActiveInIntervals$X3)
colnames(newsortprocessesdf)[colnames(newsortprocessesdf)=="ActorsActiveInIntervals$X3"] <-
"ActorsActive"
plot(newsortprocessesdf$ActorsActive, type="h", lwd=3, col="purple", main='Actors per phase',
xlab='Phases', ylab='Number of actors', axes=FALSE, frame.plot=TRUE)
#lines(newsortprocessesdf$ActorsActive, type="o")
Axis(side=2, labels=TRUE)
procnames <- as.vector(newsortprocessesdf$Label)
procnames
text(newsortprocessesdf$ActorsActive, labels =procnames, cex=0.5, pos=3, col="dimgray")

# Relate the process duration to the number of involved actors:
plot(newsortprocessesdf$Duration, newsortprocessesdf$ActorsActive, type="p", lwd=1,
col="black", main='Duration versus number of actors',
xlab='Phase duration in days', ylab='Number of actors', axes=TRUE, frame.plot=TRUE)
abline(lm(newsortprocessesdf$ActorsActive~newsortprocessesdf$Duration), col="red") #
Regression line
lines(lowess(newsortprocessesdf$Duration, newsortprocessesdf$ActorsActive, f = 2/3),
col="blue") # Local Regression
legend(83, 13.5, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(newsortprocessesdf$Label)
```

```
text(newsortprocessesdf$Duration, newsortprocessesdf$ActorsActive, labels =durnames, cex=0.5,
pos=3, col="dimgray")

# General overview of the project team size per phase:
setwd("~/Dropbox/PHD/R")
source("4Loop.R")
datesProcesses <- listOfDates (processesdf)
#
RelativeSize <- actorsdf$ProjTeamSize/actorsdf$OrganSize
actorsdf <- cbind(actorsdf, RelativeSize)
#
EmployeeProjTeamSize <- createTuples(datesProcesses,actorsdf,findSizeAbs)
EmployeeProjTeamSize
#
EmployeeRelativeSize <- createTuples(datesProcesses,actorsdf,findSizeRel)
EmployeeRelativeSize
#
sizeprocessesdf <- cbind(sortprocessesdf,EmployeeProjTeamSize$X3, EmployeeRelativeSize$X3)
colnames(sizeprocessesdf)[colnames(sizeprocessesdf)=="EmployeeProjTeamSize$X3"] <-
"AbsoluteSize"
colnames(sizeprocessesdf)[colnames(sizeprocessesdf)=="EmployeeRelativeSize$X3"] <-
"RelativeSize"
sizeprocessesdf

# Relate the process duration to the ABSOLUTE number of involved employees:
plot(sizeprocessesdf$Duration, sizeprocessesdf$AbsoluteSize, type="p", lwd=1, col="black",
main='Duration versus absolute size of project team',
xlab='Phase duration in days', ylab='Absolute size of project team', axes=TRUE, frame.
plot=TRUE)
abline(lm(sizeprocessesdf$AbsoluteSize~sizeprocessesdf$Duration), col="red") # Regression line
lines(lowess(sizeprocessesdf$Duration, sizeprocessesdf$AbsoluteSize, f = 2/3), col="blue") #
Local Regression
legend(83, 13.5, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(sizeprocessesdf$Label)
text(sizeprocessesdf$Duration, sizeprocessesdf$AbsoluteSize, labels =durnames, cex=0.5, pos=3,
col="dimgray")

# Relate the process duration to the RELATIVE number of involved employees:
plot(sizeprocessesdf$Duration, sizeprocessesdf$RelativeSize, type="p", lwd=1, col="black",
main='Duration versus relative size of project team',
xlab='Phase duration in days', ylab='Relative size of project team', axes=TRUE, frame.
plot=TRUE)
abline(lm(sizeprocessesdf$RelativeSize~sizeprocessesdf$Duration), col="red") # Regression line
lines(lowess(sizeprocessesdf$Duration, sizeprocessesdf$RelativeSize, f = 2/3), col="blue") #
Local Regression
legend(83, 13.5, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(sizeprocessesdf$Label)
text(sizeprocessesdf$Duration, sizeprocessesdf$RelativeSize, labels =durnames, cex=0.5, pos=3,
col="dimgray")

# General overview of the product entities per phase:
newsortprocessesdf2 <- cbind(sortprocessesdf,ProductsActiveInIntervals$X3)
colnames(newsortprocessesdf2)[colnames(newsortprocessesdf2)=="ProductsActiveInIntervals$X3"]
<- "ProductsActive"
```

```
plot(newsortprocessesdf2$ProductsActive, type="h", lwd=3, col="aquamarine3", main='Products
per phase',
xlab='Phases', ylab='Number of products', axes=FALSE, frame.plot=TRUE)
Axis(side=2, labels=TRUE)
procnames <- as.vector(newsortprocessesdf2$Label)
procnames
text(newsortprocessesdf2$ProductsActive, labels =procnames, cex=0.5, pos=3, col="dimgray")

#Adjacency list processes:
adjaprocessesdf <- cbind(newsortprocessesdf, newsortprocessesdf2$ProductsActive)
colnames(adjaprocessesdf)[colnames(adjaprocessesdf)=="newsortprocessesdf2$ProductsActive"] <-
"ProductsActive"
# Sum the nodes up:
adjaprocessesdf$Total <- with(adjaprocessesdf, ActorsActive+ProductsActive)
# exclude 3rd variable
newadjaprocessesdf <- adjaprocessesdf[c(1:5,10:13)]
newadjaprocessesdf
# "Print" table in plot window"
plot(1, axes=FALSE, xlab="", ylab="", main="Processes adjacency list")
text(0.55, 0.9, cex=0.7, paste(capture.output(newadjaprocessesdf), collapse='\n'), pos=4,
family="mono")
```

Script for the analysis of the network's 'edges':

```
setwd("~/Dropbox/PhD/R/Helling-R")

# File input (edges):
gephinodes <- read.csv(file="Helling-20150330-Nodes.csv",sep=",",head=TRUE)
gephinodes
gephiedges <- read.csv(file="Helling-20150330-Edges.csv",sep=",",head=TRUE)

# Focus on the actors and the processes:
actorsdf <- subset(gephinodes, NodeColor=='Actors')
actorsdf

processesdf <- subset(gephinodes, NodeColor=='Processes')
processesdf

# Count the outgoing & incoming edges for every actor:
actorsIds <- actorsdf$Id
sourcesIds <- table(gephiedges$Source) #Table of frequencies for Sources or Outgoing
targetsIds <- table(gephiedges$Target) #Table of frequencies for Targets or Incoming

countactor <- matrix(ncol=3, nrow=length(actorsIds) )
for (i in 1:length(actorsIds) ) {
id <- actorsIds[i]
countactor[i,1] = id
if (id %in% gephiedges$Source) countactor[i,2] = sourcesIds[names(sourcesIds)==id]
else countactor[i,2] = 0
if (id %in% gephiedges$Target) countactor[i,3] = targetsIds[names(targetsIds)==id]
else countactor[i,3] = 0
}
countactordf <- data.frame(countactor)
countactordf

# Count the type of role (initiator, enabler, executor) for every actor:
```

```
rolelabels <- gephiedges$Label
countrole <- matrix(ncol=4, nrow=length(actorsIds) )
for (i in 1:length(actorsIds) ) {
id <- actorsIds[i]
countrole[i,1] = id
# FILTER with [the '==' will pick up any NA as well as "hesc", whereas %in% won't.
withIdAsSource <- gephiedges[gephiedges$Source %in% c( id),]
withIdAsTarget <- gephiedges[gephiedges$Target %in% c( id),]
initiators <- withIdAsSource[withIdAsSource$Label %in% c("Initiator"),]
enablers <- withIdAsSource[withIdAsSource$Label %in% c("Enabler"),]
executors <- withIdAsTarget[withIdAsTarget$Label %in% c("Executor"),]
countrole[i,2] = nrow(initiators)
countrole[i,3] = nrow(enablers)
countrole[i,4] = nrow(executors)
}
countroledf <- data.frame(countrole)
countroledf

# Count the outgoing & incoming edges for every process:
ProcessesIds <- processesdf$Id

countprocess <- matrix(ncol=3, nrow=length(ProcessesIds) )
for (i in 1:length(ProcessesIds) ) {
id <- ProcessesIds[i]
countprocess[i,1] = id
if (id %in% gephiedges$Source) countprocess[i,2] = sourcesIds[names(sourcesIds)==id]
else countprocess[i,2] = 0
if (id %in% gephiedges$Target) countprocess[i,3] = targetsIds[names(targetsIds)==id]
else countprocess[i,3] = 0
}
countprocessdf <- data.frame(countprocess)
countprocessdf

# Add and rename the incoming & outgoing edges for every actor:
ioactorsdf <- cbind(actorsdf,countactordf$X2, countactordf$X3)
colnames(ioactorsdf)[colnames(ioactorsdf)=="countactordf$X2"] <- "Outgoing"
colnames(ioactorsdf)[colnames(ioactorsdf)=="countactordf$X3"] <- "Incoming"
ioactorsdf

ioprocessesdf <- cbind(processesdf,countprocessdf$X2, countprocessdf$X3)
colnames(ioprocessesdf)[colnames(ioprocessesdf)=="countprocessdf$X2"] <- "Outgoing"
colnames(ioprocessesdf)[colnames(ioprocessesdf)=="countprocessdf$X3"] <- "Incoming"
ioprocessesdf

# Overview of interactions... among the actors:
plot(ioactorsdf$Outgoing, type="o", pch=19, lty=3, main='Interactions per actor',
xlab='Actors', ylab='Number of interactions', axes=FALSE, col="red", frame.plot=TRUE)
Axis(side=2, labels=TRUE)
legend(12.5, 6.15, c("Outgoing","Incoming"), pch=19, col=c("red", "blue"), cex=0.55,
xjust=0.5, title="Legend")
actornames <- as.vector(ioactorsdf$Label)
text(ioactorsdf$Outgoing, labels=actornames, cex=0.4, pos=1, offset= -0.5, col="17")
par(new=TRUE)
plot(ioactorsdf$Incoming, type="o", pch=19, lty=3, main='Interactions per actor',
xlab='Actors', ylab='Number of interactions', axes=FALSE, col="blue",frame.plot=TRUE)
text(ioactorsdf$Incoming, labels=actornames, cex=0.4, pos=1, offset= -0.5, col="17")
```

```
# Sum the types of interactions:
ioactorssum <- ioactorsdf
ioactorssum$Total <- with(ioactorsdf, Outgoing+Incoming)
ioactorssum
# exclude 3rd variable
newioactorssum <- ioactorssum[c(-3)]
plot(1, axes=FALSE, xlab="", ylab="", main="Actors adjacency list")
text(0.55, 0.9, cex=0.7, paste(capture.output(newioactorssum), collapse='\n'), pos=4,
family="mono")

#Relation between the number of interactions versus the (absolute) number of each project team
members:
plot(ioactorssum$ProjTeamSize, ioactorssum$Total, type="p", lwd=1, col="black",
main='Interactions versus absolute size of project team',
xlab='Size of project team (absolute)', ylab='Number of interactions', axes=TRUE, frame.
plot=TRUE)
abline(lm(ioactorssum$Total~ioactorssum$ProjTeamSize), col="red") # Regression line
lines(lowess(ioactorssum$ProjTeamSize, ioactorssum$Total, f = 3/5), col="blue") # Local
Regression
legend(14, 10.2, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(ioactorssum$Label)
text(ioactorssum$ProjTeamSize, ioactorssum$Total, labels=durnames, cex=0.5, pos=3,
col="dimgray")

#Relative size of every organization %
RelativeSize <- ioactorssum$ProjTeamSize/ioactorssum$OrganSize
ioactorssum2 <- cbind(ioactorssum, RelativeSize)

#Relation between the number of interactions vs the (relative) number of each team:
plot(ioactorssum2$RelativeSize, ioactorssum2$Total, type="p", lwd=1, col="black",
main='Interactions versus relative size of project team',
xlab='Size of project team (relative)', ylab='Number of interactions', axes=TRUE, frame.
plot=TRUE)
abline(lm(ioactorssum2$Total~ioactorssum2$RelativeSize), col="red") # Regression line
lines(lowess(ioactorssum2$RelativeSize, ioactorssum2$Total, f = 3/5), col="blue") # Local
Regression
legend(9, 0.1, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(ioactorssum2$Label)
text(ioactorssum2$RelativeSize, ioactorssum2$Total, labels=durnames, cex=0.5, pos=3,
col="dimgray")

#TRUE & FALSE values as colour vector:
typeof(ioactorssum2$SCPosition)
ioactorssum2$SCPosition
colTrueFalse <- as.vector(ioactorssum2$SCPosition)
colTrueFalse2 <- replace(colTrueFalse, colTrueFalse==FALSE, "violet")
colTrueFalse3 <- replace(colTrueFalse2, colTrueFalse2==TRUE, "springgreen3")
colTrueFalse3

#Relation between the number of interactions versus the actor's position in the SC:
plot(ioactorssum2$Total, type="p", lwd=1, col=colTrueFalse3, main='Total interactions of each
actor in the SC',
xlab='Actor', ylab='Number of interactions', axes=FALSE, frame.plot=TRUE)
Axis(side=2, labels=TRUE)
durnames <- as.vector(ioactorssum2$Label)
```

```
text(ioactorssum2$Total, labels=durnames, cex=0.5, pos=3, col="dimgray")
legend(14, 10.2, c("Internal","External"), pch="o", col=c("springgreen3", "violet"), cex=0.55,
xjust=0.5, title="Legend")

#Boxplot of ... among actors:
sumioactors<-ioactorsdf$Outgoing+ioactorsdf$Incoming
sumactorsdf <- cbind(ioactorsdf,sumioactors)
colnames(sumactorsdf)[colnames(sumactorsdf)=="sumioactors"] <- "Total"
iototaldf <- subset(sumactorsdf, select = Outgoing:Total)
boxplot(iototaldf, main='Overview of actors interactions - Case#1', xlab='Type of
interaction', ylab='Number of interactions')
# Subseting: http://www.ats.ucla.edu/stat/r/faq/subset_R.htm

# ... during the SORTED processes:
sortedStart <- as.numeric(ioprocessesdf$Start, Sys.time())
numioprocessesdf <- cbind(ioprocessesdf,sortedStart)
sortioprocessesdf <- numioprocessesdf[order(numioprocessesdf$sortedStart), ]
sortioprocessesdf
plot(sortioprocessesdf$Outgoing, type="o", pch=19, lty=1, main='Interactions per phase',
xlab='Phases', ylab='Number of interactions', axes=FALSE, col="magenta", frame.plot=TRUE)
Axis(side=2, labels=TRUE)
legend(12.5, 6.15, c("Outgoing","Incoming"), pch=19, col=c("magenta", "green3"), cex=0.55,
xjust=0.5, title="Legend")
processnames <- as.vector(sortioprocessesdf$Label)
text(sortioprocessesdf$Outgoing, labels=processnames, cex=0.4, pos=1, offset= -0.5, col="17")
par(new=TRUE)
plot(sortioprocessesdf$Incoming, type="o", pch=19, lty=1, main='Interactions per phase',
xlab='Phases', ylab='Number of interactions', axes=FALSE, col="green3",frame.plot=TRUE)
text(sortioprocessesdf$Incoming, labels=processnames, cex=0.4, pos=1, offset= -0.5, col="17")

# Overview of the types of stakeholders' roles:
plot(countroledf$X2, type="o", pch=19, lty=3, main='Frequency of roles per actor',
xlab='Actors', ylab='Number of appearence', axes=FALSE, col="green", frame.plot=TRUE)
Axis(side=2, labels=TRUE)
legend(15.5, 5.15, c("Initiator","Enabler","Executor"), pch=19, col=c("green", "blue","red"),
cex=0.55, xjust=0.5, title="Legend")
actornames <- as.vector(ioactorsdf$Label)
par(new=TRUE)
plot(countroledf$X3, type="o", pch=19, lty=3, main='Frequency of roles per actor',
xlab='Actors', ylab='Number of appearence', axes=FALSE, col="blue",frame.plot=TRUE)
par(new=TRUE)
plot(countroledf$X4, type="o", pch=19, lty=3, main='Frequency of roles per actor',
xlab='Actors', ylab='Number of appearence', axes=FALSE, col="red",frame.plot=TRUE)
text(countroledf$X4, labels=actornames, cex=0.4, pos=1, offset= -0.5, col="17")

#Load datasets from the "..Nodes.R" here:

#FOR LOOP
setwd("~/Dropbox/PHD/R")
source("4Loop.R")
datesProcesses <- listOfDates (processesdf)
print(datesProcesses)

initiations <- gephiedges[gephiedges$Label %in% c("Initiator"),]
enablements <- gephiedges[gephiedges$Label %in% c("Enabler"),]
executions <- gephiedges[gephiedges$Label %in% c("Executor"),]
```

```
sortprocessesdf2 <- sortprocessesdf[c(1:5,10)]
sortprocessesdf2
processesdfDetails <- sortprocessesdf2
processesdfDetails$inits <- 0
processesdfDetails$enabs <- 0
processesdfDetails$execs <- 0

for (i in 1:nrow(processesdfDetails) ) {
start<- as.Date(processesdfDetails[i,4])
print(typeof(start))
end<- as.Date(processesdfDetails[i,5])
print(end)
processesdfDetails[i,7] = findRoles(start,end,initiations)
processesdfDetails[i,8] = findRoles(start,end,enablements)
processesdfDetails[i,9] = findRoles(start,end,executions)
}
processesdfDetails

# Sum the types of interactions up:
processesdfDetails$Sum <- with(processesdfDetails, inits+enabs+execs)
processesdfDetails

# Relate the process duration to the number of interactions:
plot(processesdfDetails$Duration, processesdfDetails$Sum, type="p", lwd=1, col="black",
main='Duration versus number of interactions',
xlab='Phase duration in days', ylab='Number of interactions', axes=TRUE, frame.plot=TRUE)
abline(lm(processesdfDetails$Sum~processesdfDetails$Duration), col="red") # Regression line
lines(lowess(processesdfDetails$Duration, processesdfDetails$Sum, f = 3/5), col="blue") #
Local Regression
legend(85, 12, c("Regression line","Local regression"), pch="-", col=c("red", "blue"),
cex=0.55, xjust=0.5, title="Legend")
durnames <- as.vector(processesdfDetails$Label)
text(processesdfDetails$Duration, processesdfDetails$Sum, labels=durnames, cex=0.5, pos=3,
col="dimgray")
```

Script for the analysis of the 'for-loop':

```
setwd("~/Dropbox/PhD/R/Helling-R")

# Sorted array of dates from the processes' Start and End:
listOfDates <- function (df) {
s <- as.character(df$Start)
s1<-as.Date(s)
e <- as.character(df$End)
e1<- as.Date(e)
total <- c(s1,e1)
total <- unique(total)
total <- sort(total)
}

# Dataframe of the period (Start,End) and count of active entities:
createTuples <- function(lista,df,findFunction){
variables <- 3
iterations <-length(lista)-1
output <- matrix(ncol=variables, nrow=iterations)
```

```
for (i in 1:iterations){
start <-lista[i]
output[i,1] = as.Date(lista[i])
output[i,2] = lista[i+1]
output[i,3] = findFunction(lista[i],lista[i+1],df)
}
output <- data.frame(output)
output$X1<-as.Date(output$X1, origin="1970-01-01")
output$X2<-as.Date(output$X2, origin="1970-01-01")
return(output)
}

# Find if an element (with start and end field) is active for a specific time period
(start,end):
findUsers <- function(start,end,df) {
counter<-0
for (i in 1:nrow(df) ) {
elem <- df[i,]
s<- as.character(elem$Start)
e <- as.character(elem$End)
s1<-as.Date(s)
e1<-as.Date(e)
if ((start -s1>=0) && (e1 - end>=0)){
counter<-counter+1
}
}
return(counter)
}

#findSizeProjTeam
findSizeProjTeam <- function(df, label){
elem <- df[df$Label %in% c(label), ]
return(elem$ProjTeamSize)
}

#findSizeRelative
findSizeRelative <- function(df, label){
elem <- df[df$Label %in% c(label), ]
return(elem$RelativeSize)
}

# Find project team size for a specific time period (start,end):
findSizeAbs <- function(start,end,df) {
counter<-0
for (i in 1:nrow(df) ) {
elem <- df[i,]
print(elem)
s<- as.character(elem$Start)
e <- as.character(elem$End)
s1<-as.Date(s)
e1<-as.Date(e)
if ((start -s1>=0) && (e1 - end>=0)){
label <- as.character(elem$Label)
counter<-counter+findSizeProjTeam(df,label)
}
}
return(counter)
```

```
}

# Find relative size for a specific time period (start,end):
findSizeRel <- function(start,end,df) {
counter<-0
for (i in 1:nrow(df) ) {
elem <- df[i,]
print(elem)
s<- as.character(elem$Start)
e <- as.character(elem$End)
s1<-as.Date(s)
e1<-as.Date(e)
if ((start -s1>=0) && (e1 - end>=0)){
label <- as.character(elem$Label)
counter<-counter+findSizeRelative(df,label)
}
}
return(counter)
}

findRoles <- function(start,end,df) {
counter<-0
for (i in 1:nrow(df) ) {
elem <- df[i,]
s<- as.character(elem$Start)
e <- as.character(elem$End)
s1<-as.Date(s)
e1<-as.Date(e)
if ((start<=s1) && (e1<=end)){
counter<-counter+1
}
}
return(counter)
}
```

Appendix C

The questions for the semi-structured interviews with the various actors for each case were:

- How could you describe your position/function in your company?
- Could you give me some background information about the project (e.g. goals, challenges, performance)?
- What was the motivation of your company on engaging to Supply Chain partnerships and are there any benefits and challenges you have observed in relation to them?
- What is your main role (i.e. your rights, responsibilities, expectations, norms and behaviours) regarding the project's Supply Chain partnership?
- What is in your view, the main role of the other parties: architect, client, contractor, structural engineer, and supplier(s) (i.e. rights, duties, responsibilities, expectations, norms and behaviours) regarding the project's Supply Chain partnership?
- What was the motivation of your company on applying BIM and are there any benefits and challenges you have observed in relation to it?
- What is your main role (i.e. your rights, responsibilities, expectations, norms and behaviours) regarding BIM implementation in this project?
- What is in your view, the main role of the other parties: architect, client, contractor, structural engineer, and supplier(s) (i.e. rights, duties, responsibilities, expectations, norms and behaviours) regarding BIM implementation in this project?
- Considering the performance of the project what would you desire to change for a future project?

Appendix D

Protocol for 'External Validation' Workshop

Date, time, and place

The 'external validation' workshop will take place on June 6th from 9.30 to 12.00 at the Faculty of Architecture (Bouwkunde), Julianalaan 134, 2628BL, Delft. In total 7 experts who are active in the wider domains of 'BIM' and/or 'Ketensamenwerking'/Supply Chain Management (SCM) will participate. The workshop will take place in room: BK.01.West.060.

Objectives

The objectives of this workshop are to validate the research findings, which have been developed during the PhD research, and discuss under which conditions these findings would be applicable and transferable to other contexts. For preparation, the experts are encouraged to read this workshop protocol and, if desired, the 'PhD Summary' of the PhD research in "Supply Chain integration with BIM".

During the workshop, a short presentation on the PhD research will first take place. This presentation will focus on the initial research objectives and the final findings, but will not elaborate on the research methodology of intermediate studies. Afterwards, some statements will be presented and will be followed by questions, such as:

- "Why and under which conditions are these results of the PhD research relevant?"
- "What is the applicability of this PhD research in the construction sector?"
- "What is missing in the current version of this PhD research and could be included?"

Participants

There are three active roles in the workshop: facilitator, candidate, and panel of experts

Facilitator: The workshop facilitator is familiar to the PhD research but impartial, and would use this workshop protocol to ensure that the discussions are heading in the right direction and that the time is managed appropriately. The facilitator would for example ask: "Do you have any other comment/question about the last point?" and would steer the discussion accordingly.

PhD candidate: At the beginning of the meeting, the PhD candidate will present the research and the statements to be discussed. Afterwards, the PhD candidate will be an observer of the discussions with the panel of experts, and ideally would not intervene to defend, but only to explain or clarify.

Experts: The workshop will be largely benefitted from the generous participation of experts and professionals in construction, who could be familiar with BIM and/or SCM.

Expected outcomes

Upon the workshop's completion, the research findings would be discussed and potentially validated or enriched by the experts. The questions to the experts will be structured to allow for argumentation on the conditions. Their feedback will be recorded (audio) and will be transcribed and used in the dissertation. The outcome would be a set of statements about the extent to which the findings could be generalized. The participants may choose to remain anonymous during the discussion of the workshop in the PhD thesis.

Curriculum Vitae

1984	Born on November 7th, in Athens, Greece
2002 – 2008	Dipl.-Ing. (*Cum Laude*) in Architectural Engineering, NTUA, Greece
2005 – 2006	Intern Architect at Octas Co., Athens, Greece & Gulf Precast Co., Dubai, U.A.E.
2008	Architect at Emergency Relief Fund, Ministry of Finance, Athens, Greece
2008 – 2010	Architect at A. N. Tombazis and Associate Architects, Athens, Greece
2010 – 2012	MSc (*Cum Laude*) in Architecture, TU Delft, the Netherlands
2012	Architect at DeZwarteHond, Rotterdam, the Netherlands
2012 – 2016	PhD Candidate and Assistant Lecturer at TU Delft, the Netherlands
Since 2016	Lecturer in Building Information Modelling and Management at University College London, UK

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Publications

Papadonikolaki, E. (2016, November 7-9). Managing Actors and Building Information for Supply Chain Integration. Paper presented at the ASCAAD 2016 conference, London, UK.

Papadonikolaki, E., Vrijhoef, R., & Wamelink, J.W.F. (In 1st Revision). *Emerging intra- and inter-organisational relations in BIM-enabled SC partnerships*. Invited manuscript for a special issue on "*Using building information: organisational and policy implications of the digitisation of buildings*".

Papadonikolaki, E., Verbraeck, A., & Wamelink, J.W.F. (In 2nd Revision). *Formal and informal relations within BIM-enabled Supply Chain Partnerships*. Invited manuscript for a special issue on "*Social Networks in construction*".

Aibinu, A. & **Papadonikolaki, E.** (2016, September 5-7). *BIM Implementation and Project Coordination in Design-Build Procurement.* Paper presented at the Proceedings of the 32nd Annual ARCOM Conference, Manchester, UK.

Papadonikolaki, E., Vrijhoef, R., & Wamelink, J.W.F. (2016). *The interdependences of BIM and Supply Chain Partnering: Empirical Exploration*. Architectural Engineering and Design Management. DOI: http://10.1080/17452007.2016.1212693

Aibinu, A. & **Papadonikolaki, E.** (2016, September 7-9). *A comparative case study of coordination mechanisms in Design and Build BIM-based projects*. Paper presented at the Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus.

Berlo, L., van & **Papadonikolaki, E.** (2016 September 7-9). *Facilitating the BIM coordinator and empowering the suppliers with automated data compliance checking*. Paper presented at the Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus.

Papadonikolaki, E. & Oel, C., van. ((2016, September 5-7). *The actors' perceptions and expectations of their roles in BIM-based collaboration*. Paper presented at the Proceedings of the 32nd Annual ARCOM Conference, Manchester, UK.

Papadonikolaki, E., Vrijhoef, R., & Wamelink, J.W.F. (2015). *Supply chain integration with BIM: A graph-based model*. Structural Survey, 33(3), 257-277.

Papadonikolaki, E., Vrijhoef, R. & Wamelink, J.W.F. (2015, September 5-7). *BIM adoption in integrated supply chains: a multiple case study*. Paper presented at the 31st Annual ARCOM Conference, Lincoln, UK.

Papadonikolaki, E., Vrijhoef, R. & Wamelink, J.W.F. (2015, September 7-9). *A BIM-based supply chain model for AEC*. Paper presented at the Building Information Modelling (BIM) in Design, Construction and Operations, Bristol, UK.

Papadonikolaki, E., Koutamanis, A., & Wamelink, J.W.F. (2014, September 17-19). *A Global Framework for Modelling Supply Chains in AEC*. Paper presented at the Proceedings of the 10th European Conference on Product and Process Modelling (ECPPM 2014), Vienna, Austria.

Papadonikolaki, E., Koutamanis, A., & Wamelink, J.W.F. (2014, September 17-19). *The Utilisation of BIM as a Project Management Tool*. Paper presented at the Proceedings of the 10th European Conference on Product and Process Modelling (ECPPM 2014), Vienna, Austria.

Papadonikolaki, E., & Verbraeck, A. (2014, September 17-19). *Modelling and Simulation Research for Construction Supply Chains*. Paper presented at the Proceedings of the 10th European Conference on Product and Process Modelling (ECPPM 2014), Vienna, Austria.

Papadonikolaki, E., Koutamanis, A., & Wamelink, J.W.F. (2013, September 18-20). *Attaining Performance with Building Information Modelling*. Paper presented at the Computation and Performance - Proceedings of the 31st eCAADe Conference, Delft, Netherlands.