# Product Information Quality

## A sustainability challenge in design and construction

Bahrami, Soheila

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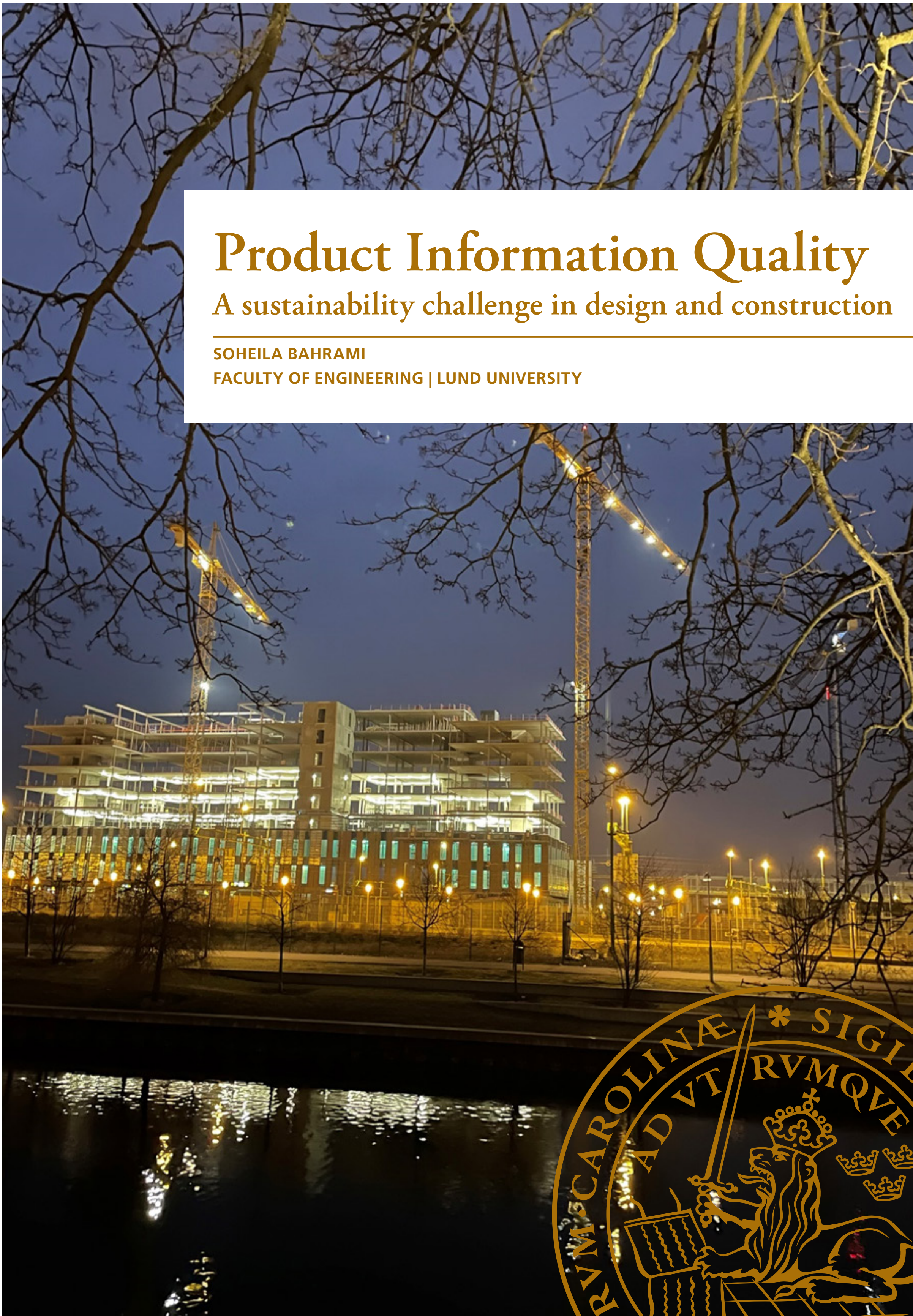
SOHEILA BAHRAMI
FACULTY OF ENGINEERING | LUND UNIVERSITY



# Product Information Quality

## A sustainability challenge in design and construction

Soheila Bahrami

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Product Information Quality: A sustainability challenge in design and construction

**Abstract**

The adverse consequences of building product performance pose sustainability problems for the built environment. Effective approaches to these problems require a clear understanding of building product information and its provision by manufacturers. This is an essential need for sustainable growth in industrialized construction, a system characterized by the expanded role of the manufacturing sector. Furthermore, a sustainable transition to digitalization in the construction industry needs digital interfaces capable of providing the information required for sustainable design and construction.

The aim of this research is to contribute to an increased understanding of how building product information can support sustainability in the built environment. To this end, two fundamental aspects have been examined: the quality of information on the sustainability performance of building products and the usability of the digital interfaces providing such information. This research relies on critical realism and adopts a qualitative methodology to analyze and explain the mechanisms of creating and providing product information in four sequential case studies. Systems thinking and process tracing method have been applied to analyze the flow of product information in the construction industry, the operative processes that can support sustainability, and the stakeholders involved.

In the first three case studies, the operative process is the diffusion of innovative ventilation products with superior indoor environmental performance. The first case study identifies the problems affecting this process. The second and third case studies, respectively, explore how product information and information exchange on building information modeling (BIM) library platforms can support the process. Influenced by the Grenfell Tower fire in London in 2017, the fourth case identifies the product information problems that can contribute to harmful facade fires threatening sustainability in the built environment. The study examines the capabilities for avoiding the identified problems and explores how an operative process of design, manufacturing, and construction of fire-safe facades can be supported.

The findings reveal problems concerning the quality of information on the sustainability performance of products and the methods used by manufacturers for presenting such information. These problems have limited the availability and usability of the information in product databases and BIM object libraries. This defective flow of information affects the design process and can lead to unacceptable consequences such as facade fires. In addition, the inefficient methods of supplying product information have impeded the adoption of innovative products with improved sustainability performance. To address these issues, this research proposes the standardization of product information in collaboration with effective legislation and establishes a framework for evaluating the provision of information on the sustainability performance of building products.

The theoretical contributions of this work include five tools: (1) a model for applied critical realism towards sustainability, (2) a matrix for the qualitative analysis of BIM object library platforms, (3) a matrix for evaluating the quality of information and digital interfaces, (4) a model of the functions of the standards on product information, and (5) a conceptual model of product information for sustainable design and construction.

**Keywords** Sustainability, Product information, Building design, Industrialized construction, Standardization

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*To Arya, Amir, and my parents*

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*Soheila Bahrami*

Lund, October 2021

# Abstract

The adverse consequences of building product performance pose sustainability problems for the built environment. Effective approaches to these problems require a clear understanding of building product information and its provision by manufacturers. This is an essential need for sustainable growth in industrialized construction, a system characterized by the expanded role of the manufacturing sector. Furthermore, a sustainable transition to digitalization in the construction industry needs digital interfaces capable of providing the information required for sustainable design and construction.

The aim of this research is to contribute to an increased understanding of how building product information can support sustainability in the built environment. To this end, two fundamental aspects have been examined: the quality of information on the sustainability performance of building products and the usability of the digital interfaces providing such information. This research relies on critical realism and adopts a qualitative methodology to analyze and explain the mechanisms of creating and providing product information in four sequential case studies. Systems thinking and process tracing method have been applied to analyze the flow of product information in the construction industry, the operative processes that can support sustainability, and the stakeholders involved.

In the first three case studies, the operative process is the diffusion of innovative ventilation products with superior indoor environmental performance. The first case study identifies the problems affecting this process. The second and third case studies, respectively, explore how product information and information exchange on building information modeling (BIM) library platforms can support the process. Influenced by the Grenfell Tower fire in London in 2017, the fourth case study identifies the product information problems that can contribute to harmful facade fires threatening sustainability in the built environment. The study examines the capabilities for avoiding the identified problems and explores how an operative process of design, manufacturing, and construction of fire-safe facades can be supported.

The findings reveal problems concerning the quality of information on the sustainability performance of products and the methods used by manufacturers for presenting such information. These problems have limited the availability and usability of the information in product databases and BIM object libraries. This defective flow of information affects the design process and can lead to unacceptable consequences such as facade fires. In addition, the inefficient methods of supplying product information have impeded the adoption of innovative products with improved sustainability performance. To address these issues, this research proposes functional standardization of product information in collaboration with

effective legislation and establishes a framework for evaluating the provision of information on the sustainability performance of building products.

The theoretical contributions of this work include five tools: (1) a model for applied critical realism towards sustainability, (2) a matrix for the qualitative analysis of BIM object library platforms, (3) a matrix for evaluating the quality of information and digital interfaces, (4) a model of the functions of the standards on product information, and (5) a conceptual model of product information for sustainable design and construction.

# Populärvetenskaplig sammanfattning

En byggnad innehåller många delar och olika komponenter som sammantaget ska tillhandahålla en funktion. För att en byggnad ska fungera som det är tänkt måste alla delar fungera tillsammans. Det finns negativa effekter som kan uppkomma om inte byggdelarnas sammantagna egenskaper beaktas, exempelvis fasadbränder. Detta medför i sin tur ett hållbarhetsproblem för den byggda miljön. För att kunna sätta samman en byggnad som fungerar måste man förstå hur de olika delarna samverkar. Det innebär att alla företag som tillverkar byggmaterial, byggdelar och komponenter måste ange all den information som behövs för att kunna bedöma om det går att använda ett visst material eller en komponent i en byggnad om kraven ska tillfredsställas. Informationen måste dessutom leva vidare i bearbetningen från de tidiga skedena och vidare i projekteringen, byggproduktionen och förvaltningen. Detta gör att förståelsen för byggproduktinformation och hur denna tillhandahålls av leverantörerna är viktig för att det som byggs uppnår den prestanda som krävs. Detta är ett väsentligt kunskapsbehov för att främja en hållbar tillväxt. För det industrialiserade byggandet är det extra viktigt eftersom det till kräver att leverantörernas roll ökar. Informationen, som är digitaliserad måste även kunna föras vidare i pålitliga digitala gränssnitt för att erhålla en hållbar tillväxt i industrialiserat byggande.

Syftet med denna studie är att bidra till en ökad förståelse för hur byggproduktinformation kan stödja hållbarhet i den byggda miljön. I detta arbete har två grundläggande aspekter undersökts: kvaliteten på information om hållbarhetsprestanda för byggprodukter och användbarheten på gränssnitten som ger sådan information.

I undersökningen har olika fallstudier genomförts för att förklara vilka mekanismer som skapar informationen och på vilket sätt informationen flödar mellan olika intressenter som ska hantera den. I de första tre fallstudierna undersöktes spridningen av information gällande innovativa ventilationsprodukter med överlägsen inomhus miljökvalitetsprestanda. Den första fallstudien identifierade de problem som berör informationsflödet. Den andra och tredje fallstudien undersökte på vilket sätt produktinformation och informationsutbyte sker i relation till standardisering och genom BIM-biblioteksplattformar samt hur processerna kan stödjas. Den fjärde fallstudien utgick ifrån katastrofscenarios som Grenfell Tower -branden i London 2017, och identifierar vilka produktinformationsproblem som kan orsaka brister vilka kan leda till bränder som i sin tur äventyrar hållbarheten i byggandet. Fallstudien kartlägger även vilka möjligheter som kan utnyttjas för att undvika problem och ger förslag på operativa rutiner i byggandets olika skeden, projektering, tillverkning och produktion, kan stödjas för brandsäkra fasader.

Resultaten visar att det finns problem som behöver lösas när det gäller kvaliteten på information om hållbarhet för produkters prestanda och de metoder som används av tillverkare för att presentera sådan information. Studierna har avgränsats till tillgängligheten och användbarheten för den information som tillhandahålls om produkterna i databaser och BIM -objektbibliotek. När det förkommer den här typen av brister i informationsflödet så kan det påverka den färdiga byggnaden och leda till oacceptabla konsekvenser såsom fasadbränder. Resultatet visar också att det finns hinder för spridningen av information om innovativa produkter med förbättrad hållbarhetsprestanda och vilket påverkar hur byggnader kan utformas och detta kan leda till konsekvenser som hotar hållbarheten i den byggda miljön. För att ta itu med dessa frågor föreslås att produktinformation standardiseras och stöds av lagstiftning. Denna avhandling föreslår även en ram för utvärdering av information om byggnadens hållbarhetsprestanda. De teoretiska bidragen från detta arbete inkluderar fem verktyg: (1) en modell för tillämpad kritiskrealism mot hållbarhet, (2) en matris för den kvalitativa analysen av BIM -biblioteksplattformar, (3) en matris för utvärdering av informationskvaliteten och digitala gränssnitt, (4) en modell av funktionerna i standarderna för produktinformation, och (5) en konceptuell modell av produktinformation för hållbar design och konstruktion.

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Paper II Innovation diffusion through standardization: A study of building ventilation products

S. Bahrami, B. Atkin, A. Landin

*Journal of Engineering and Technology Management*, 54, 56–66 (2019)

Paper III Enabling the diffusion of sustainable product innovations in BIM library platforms

S. Bahrami, B. Atkin, A. Landin

*Journal of Innovation Management* 7 (4), 106–130 (2019)

Paper IV The sustainability challenge of product information quality in the design and construction of facades: lessons from the Grenfell Tower fire

S. Bahrami, D. Zeinali

Submitted manuscript under review, *Smart and Sustainable Built Environment* Journal (2021)

# Abbreviations

| | |
|---|---|
| ACP | Aluminum Composite Panels |
| AEC | Architecture, Engineering, and Construction |
| APVP | Acoustic Performance of Ventilation Products |
| BIM | Building Information Modeling |
| BOM | Bill of Materials |
| BSI | British Standards Institution |
| CAD | Computer-aided Design |
| CEN | European Committee for Standardization |
| DCV | Demand Controlled Ventilation |
| DfMA | Design for Manufacturing and Assembly |
| EPDM | Ethylene Propylene Diene Monomer |
| EMS | Environmental Management System |
| GMFRS | Greater Manchester Fire and Rescue Service |
| HCI | Human-computer Interaction |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IBC | International Building Code |
| IPA | British Infrastructure and Projects Authority |
| ISO | International Organization for Standardization |
| MCM | Metal Composite Material |
| MEP | Mechanical, Electrical, and Plumbing |
| NBS | National Building Specification (UK) |
| NFPA | National Fire Protection Association (US) |
| PE | Polyethylene |
| PIR | Polyisocyanurate |
| PLM | Product Life cycle Management |
| QFD | Quality Function Deployment |
| QMS | Quality Management System |
| REHVA | The Federation of European Heating, Ventilation, and Air Conditioning |
| RIBA | Royal Institute of British Architects |
| SIS | Swedish Institute for Standards |
| UPVC | Unplasticized Polyvinyl Chloride |
| WHO | World Health Organization |

# 1 Introduction

For over six decades, scholars have warned against unsustainable growth (e.g., Carson, 1962; Rostow, 1960; Tilles, 1964; Meadows, 2008; Suzuki, 2021) and proposed strategies to address the social, environmental, and economic impacts of firms' functions (e.g., Elkington, 1997; Elkington, 2018; Hart and Milstein, 2003; Sulkowski et al., 2018). However, the built environment still encounters complex sustainability problems, evident in the building fires connected with sustainable design strategies (Meacham and McNamee, 2020).

Improving sustainability in the built environment is an intricate problem due to complicated chains of decisions in construction processes (Cooper and Whyte, 2018), including procurement (Bankvall et al., 2010), design (Bonner et al., 2020; Hu et al., 2020), and construction (Goulding et al., 2015; Zhou et al., 2020). In particular, the design process involves considerable complexity (Bonner et al., 2020; Hu et al., 2020; Montali, 2019, p. 14) because of the factors that interactively affect building performance.

One of these complex design problems is building ventilation design. Insufficient ventilation rate has been identified as a critical factor that contributes to virus transmission (REHVA, 2021), poor indoor air quality, and consequent problems that undermine health and work performance (European Commission, 2008; European Ventilation Industry Association, 2021), such as sick building syndrome or building-related illness (Paleologos et al., 2021). However, higher ventilation rates increase energy consumption in a building, which must be under certain limits determined by the building codes on energy performance (Van Holstein et al., 2019). In addition, high airflow rates might generate noise in ventilation systems (Ekberg, 2021) that can cause cardiovascular and psychophysiological problems (WHO, 2021).

Although optimization methods have been suggested to deal with complexities in building design (Bellamy, 2020; Polson, 2020; Wang, 2014), design failures relating to material selection indicate fundamental problems in design decisions. Representative examples are energy-efficient design strategies that have contributed to fire incidents worldwide (Meacham and McNamee, 2020). A majority of those incidents are associated with using insulation materials that can increase the thermal efficiency in buildings but are also combustible (Meacham and McNamee, 2020). It has been argued that raising energy efficiency targets in the UK fostered the use of combustible materials in the exterior walls of high-rise buildings, which has been a significant contributing factor in the rapid spread of fire across facades and its tragic consequences (McKenna et al., 2019).

A notable case of facade fires was the Grenfell Tower fire in London in 2017 that claimed the lives of 72 residents (Potton and Sutherland, 2020). The fire also caused severe environmental contamination and associated health risks (Stec et al., 2019), physical and psychological effects on survivors (Cooper and Whyte, 2018), emergency workers, and volunteers (Green et al., 2018), and psychological effects on the bereaved and witnesses (Green et al., 2018). Design and construction defects in the facade system, particularly its combustible materials, have been identified as the major causes of a very rapid spread of fire (Lane, 2018; McKenna et al., 2019). Moreover, the fire generated heavy toxic smoke and falling debris that seriously interfered with occupants' escape and firefighting measures (Lane, 2018; McKenna et al., 2019).

Building design professionals can prevent such disastrous consequences by applying systems thinking when deciding on strategies to improve the sustainability performance of buildings. Systems thinking (Arnold and Wade, 2015; Meadows, 2008; Senge and Fulmer, 1993) is particularly helpful in choosing innovative solutions because innovations involve inherent uncertainty (Rogers, 2003a, p. 14) about the new features of products (Zsifkovits and Günther, 2015). Therefore, the success of systems thinking depends on the quality and flow of information. Information holds a system together, and its flow determines how a system works (Meadows, 2008). However, poor quality of information can produce adverse effects, such as confusion (Eppler, 2006, p. III).

*Information quality* can be defined as "the degree to which the information creates value for a user in a particular application" (Talburt, 2010, p. 42), while truthfulness is recognized as the essential quality of information (Floridi, 2019a, p. 113). The criteria that are commonly used to evaluate the quality of information are accuracy, precision, currency, sufficiency, comprehensibility, timeliness, relevance, and usability (Peter et al., 2013).

The usability of digital information depends entirely on the usability of the interface (software) that provides the information. Software usability is "the extent to which a product can be used by specified users to achieve specific goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2006). Examples of specific criteria suggested for evaluating the interface usability are accessibility, traceability (Eppler, 2006, p. 68), and searchability (Whyte, 2019).

In the construction industry, the flow of information through building information modeling (BIM) is changing the interactions between various actors and transforming the project delivery models (Whyte and Hartmann, 2017). The growing recognition of BIM applications (Gao et al., 2017; Pasini et al., 2017) offers a central role to BIM object libraries. These are platform ecosystems (Parker et al., 2017d) in which BIM objects are created and provided. BIM objects contain semantic and geometric information on building products (Gao et al., 2017). In previous studies on BIM objects and libraries, researchers have investigated BIM object classifications (e.g., Pasini et al., 2017; Wu and Zhang, 2019), searchability of BIM objects (e.g., Gao et al., 2017), and interoperability of information (e.g., Farghaly, 2020). Although the quality of product information provided by manufacturers determines the usability of BIM object libraries in design for sustainability, no study to date has examined the information in BIM objects regarding the sustainability attributes of the products they represent, particularly in connection with the diffusion of innovations, a concept popularized by Rogers (2003a).

Standards on product information improve communication and the exchange of information between various stakeholders (Ho and O'Sullivan, 2015) and facilitate comparison between products (Egyedi and Ortt, 2017, p. 114). Therefore, supplying standardized information about the sustainability attributes of products can encourage purchase choices in favor of sustainability (Cho et al., 2018). These functions of standards highlight the importance of research on the standardization of building product information regarding sustainability attributes of products. Such investigation requires a holistic approach considering the interactions between BIM objects quality, the usability of BIM object libraries, and the ecosystem of BIM library platforms, which previous studies have not addressed.

However, a BIM object does not contain information about the entire life cycle of a product. Therefore, other sources of information, such as material databases, are needed in the early stages of design. In the manufacturing sector, the concept of digital twins has been developed to provide reliable information for product life cycle management systems (Lechler et al., 2020). A digital twin is defined as a dynamic virtual representation of a physical object or system across its life cycle, which provides real-time data (Bolton et al., 2018) and allows for real-time optimization (Söderberg et al., 2017). The concept of digital twins has been studied in facility operation and management (Arnold and Teicholz, 2021), prefabrication of building modules (e.g., Gerhard et al., 2020), evaluation of building control strategies (e.g., Nytsch-geusen et al., 2019), and facades in the use stage of their life cycle (e.g., Böke, 2020; Böke et al., 2020; Khajavi et al., 2019). Creating digital twins in manufacturing aims to minimize harm to users (Grieves and Vickers, 2017). Nevertheless, how its applications can enable designers to improve the sustainability performance of buildings (e.g., fire resistance) appears to be unexamined.

The need for digital forms of product information that are reliable is of particular importance in the current transition towards digitalization and industrialized construction (Andersson and Lessing, 2017). Over the past decade, industrialized construction, which is characterized by product orientation (Hall et al., 2020; Lessing and Brege, 2015; Ramaji et al., 2017) and applies modern methods of construction (Spisakova and Kozlovska, 2020), has attracted considerable attention in the construction industry (Li et al., 2020). This approach to construction facilitates information management through standardized procurement processes (Jansson, 2016) and work procedures (Eriksson et al., 2019).

Industrialized construction involves prefabrication and modularization (Jansson et al., 2018; Razkenari et al., 2020) that can accelerate construction by 50% and reduce costs by 20% (Bertram et al., 2019). However, prefabrication affects construction design management and constrains architectural work (Jansson et al., 2018) because of an expanded role of manufacturing. Gaining the advantages of modular construction requires cautiously optimizing the choice of materials and developing a thorough understanding of challenges in design, manufacturing, and assembly (Bertram et al., 2019). This highlights the importance of reliable information on building products and components.

In addition, a growing trend in industrialized construction has renewed interest in research on production-based design concepts such as design for manufacturing and assembly (DfMA) (Gao et al., 2020; Lu et al., 2020) concerning BIM processes (Alfieri et al., 2020), parametric design (Yuan et al., 2018), and facade design (Chen and Lu, 2018; Di Giuda et al., 2019). It has also generated interest in adapting the concepts and tools for managing product information in the manufacturing sector. For example, applying product life cycle management (PLM) (Gerhard et al., 2020), customizing bill of materials (BOM) (Eriksson et al., 2019; Hussamadin et al., 2020), and a BOM-based approach to structure BIM information (Mukkavaara et al., 2018) have been suggested to improve the flow of information in industrialized construction projects. These trends imply an expanded influence of the manufacturing sector over the construction industry in industrialized construction.

Despite its significant impact, fundamental questions about the quality of building product information supplied by manufacturers remain unanswered. Of particular concern is information on the sustainability performance of building products. This research develops a conceptual framework to address these various yet interrelated knowledge gaps by adopting a critical realism philosophy (Bhaskar, 2014a; Danermark et al., 2019) and systems thinking (Meadows, 2008; Senge and Fulmer, 1993).

## 1.1 Research Aim

The overall aim of this research is to enrich the understanding of building product information in support of sustainability in the built environment. To achieve this aim, this research has sought to answer the following questions through four sequential case studies presented in the appended papers.

1) How can the quality of building product information be improved to support sustainability in the built environment?

2) How can the interfaces providing building product information be improved to support sustainability in the built environment?

The objectives of the case studies are listed below.

**Case study 1**

- To examine the quality of information on the acoustic performance of an innovative ventilation system with enhanced sustainability performance
- To provide suggestions for improvements

**Case study 2**

- To explore the functions of standards on building product information in supporting the diffusion of innovative ventilation products with enhanced sustainability performance
- To identify the stakeholders involved in the supply and demand of the standards
- To provide suggestions for improvements

**Case study 3**

- To investigate the usability of BIM object libraries in support of the diffusion of innovative ventilation products with enhanced sustainability performance
- To provide suggestions for improvements

**Case study 4**

- To identify the problems associated with facade product information that led to unacceptable consequences of facade fire incidents
- To examine the quality and flow of facade product information in connection with design and construction processes, designers, and digital tools
- To provide suggestions for improvements in the creation and supply of facade product information, which can prevent unacceptable consequences of design and construction and support sustainability in the built environment

## 1.2 Delimitation of Research

Product information in this research is limited to information on the sustainability performance of ventilation products and facade products. The first three case studies focus on the ventilation product information relating to acoustic comfort because the first part of this research has been conducted as part of the Urban Tranquility project (Interreg, 2018). To apply systems thinking, acoustic performance has been studied in connection with thermal comfort, indoor air quality, energy efficiency, and carbon footprint. The fourth case study focuses on fire safety in connection with energy efficiency.

To emphasize the importance of systems thinking in sustainability research, the conceptual model of product information proposed in this research (Figure 19) includes other sustainability aspects: structural safety, electrical safety, greenhouse gas emissions, material safety and efficiency, water safety and efficiency, waste generation, visual comfort, maintainability, and security. Regarding information users, this research focuses on professionals involved in the design, performance simulations, and procurement processes during construction projects. Since a regional fund supported the Urban Tranquility project, the first three case studies are limited to Sweden. The BIM libraries studied in Case study 3, however, are used internationally. In Case study 4, the reports on fire incidents worldwide have been analyzed to design the case study, and the data has been collected from relevant sources in nine countries: Australia, Denmark, Finland, France, Italy, Sweden, the UAE, UK, and the US.

## 1.3 Selected and Adapted Definitions

The definitions selected and adapted to the purpose of this research are as follows.

| | |
|---|---|
| BIM object | A data file detailing information about the identity, dimensions, appearance, and performance of a product (BSI, 2018, p. 14) |
| Carbon footprint of a product | The net sum of greenhouse gas emissions and removals in a product system expressed as carbon dioxide equivalents based on a life cycle assessment (ISO, 2018a) |
| Data | Representations of events, people, resources, or conditions in a variety of formats, such as numbers, codes, text, graphs, or pictures (Davis, 2000, p. 71) |

| | |
|---|---|
| Diffusion of innovation | The process in which an innovation is communicated through certain channels over time among members of a social system (Rogers, 2003a, p. 5) |
| Information | Reinterpretable representation of data in a formalized manner suitable for communication, interpretation, or processing (ISO, 2018b) |
| Innovation | The new or changed object (e.g., product, process, system, service) realizing or redistributing value (ISO, 2015a) |
| Knowledge | Human or organizational asset enabling effective decisions and action in context (ISO, 2018c) |
| Life cycle | Life of the asset (product in this research) from the definition of its requirements to the termination of its use, covering its conception, development, operation, maintenance support, and disposal (ISO, 2018b) |
| Product life cycle management (PLM) | A systematic concept for the integrated management of product information and processes through the product life cycle (Saaksvuori and Immonen, 2008; Schuh et al., 2008) |

## 1.4 Publications and Author Contributions

Five publications have been produced throughout this research. The following is a list of the publications.

Paper I — Communicating the acoustic performance of innovative HVAC solutions

Authors: S. Bahrami, J. Negreira, S. Olander, A. Landin

Published in: Johansson, D. et al. (eds.), *Cold Climate HVAC 2018*, Springer Proceedings in Energy (2019) 1085–1095

Paper II — Innovation diffusion through standardization: A study of building ventilation products

Authors: S. Bahrami, B. Atkin, A. Landin

Published in: *Journal of Engineering and Technology Management* 54 (2019) 56–66

| | |
|---|---|
| Paper III | Enabling the diffusion of sustainable product innovations in BIM library platforms<br>Authors: S. Bahrami, B. Atkin, A. Landin<br>Published in: *Journal of Innovation Management* 7 (4) (2019) 106–130 |
| Paper IV | The sustainability challenge of product information quality in the design and construction of facades: lessons from the Grenfell Tower fire<br>Authors: S. Bahrami, D. Zeinali<br>Submitted manuscript under review in: *Smart and Sustainable Built Environment* Journal (2021) |
| Licentiate thesis | Diffusion of sustainable HVAC innovations in BIM platforms<br>Author: S. Bahrami<br>Division of Construction Management, Lund University (2019) |

The licentiate thesis was a compilation of Paper I and the unpublished manuscripts of Papers II and III. In each of the four case studies presented in the appended papers, the present author designed the case, collected the data, performed the analysis, and wrote the paper. In Case study 1, presented in Paper I, Juan Negreira assisted in conducting one of the interviews, analyzing the data, and writing the results. Anne Landin and Stefan Olander supervised and reviewed the work. In the case studies presented in Paper II and Paper III, Brian Atkin and Anne Landin supervised and reviewed the works, and Brian Atkin helped edit the papers. During the work on Paper IV, Davood Zeinali performed one of the trials to evaluate the usability of the National Fire Protection Association (NFPA) tool, reviewed the data analysis, and helped edit the manuscript.

## 1.5 Research Evolution

The author developed a deep interest in innovative solutions for improving sustainability in the built environment while completing a Master's program in environmental management at Lund University. The thesis work (Bahrami, 2008) explored the creative solutions in six energy-efficient buildings, including traditional natural cooling and lighting concepts as well as innovative solutions that employed those traditional concepts. Among the findings, what particularly captured attention was a significant difference between the cases in terms of adopting innovative solutions. Contrary to other cases, users in an energy-efficient building had abandoned the innovative solutions and substituted a passive cooling system with electric wall-mounted air conditioners. A comparative analysis of the in-depth interviews with the users of those buildings showed that the critical factors in adopting a new sustainable solution were the user's knowledge about the system functions and the availability of maintenance support. The author became more confident about those findings through reading Miller's (2009) fascinating book, "Selling solar", which shows how providing users with product information and technical expertise resulted in the successful diffusion of solar panels.

Upon completing a Master's degree in mechanical and materials engineering in 2015, the author investigated the problem of unexpected energy consumptions in a certified green building in Canada (Bahrami, 2015). Surprisingly, the energy consumption in the building was even higher than a similar conventional building. An interesting finding was the reverse function of the energy recovery ventilator because of the confusing information on the control system supplied by the manufacturer to the facility operators. This background provided a basis for the initial framework for this research that integrates the concepts of sustainability (Elkington, 1997; World Commission on Environment and Development, 1987) and diffusion of innovations (Rogers, 2003b) to investigate the quality and flow of building product information.

In light of the findings of the first case study, presented in Paper I, the conceptual framework is extended to include the concept of standardization (Blind, 2017; Egyedi and Ortt, 2017; Featherston et al., 2016; Ho and O'Sullivan, 2017; Swann, 2010; Tassey, 2015). The second case study identifies the central role of software companies in the flow of building product information (see Paper II). Therefore, the concept of digital platform ecosystems is added to the conceptual framework to perform the third case study presented in Paper III.

Reading about the details of the Grenfell Tower fire was a landmark in this research. As it is discussed in Paper IV, the disastrous consequences of the incident were connected to the problem of product information. To shoulder responsibility as a researcher in this field, the author chose the Grenfell Tower fire case to examine product information quality and the capabilities for avoiding such failures and supporting sustainability in the built environment. Therefore, in the fourth case study, the operative process is extended from the diffusion of innovations, which has been applied in the first three case studies, to the design, manufacture, and construction of building components.

Case studies 1, 2, and 3 focus on the quality of information on the sustainability performance of innovative products as a factor influencing the recognition and adoption of those products. In the fourth case study, the emphasis is on the fire safety performance to highlight the significant risks of deficient information regarding the sustainability performance of products. The findings from Case study 4 apply to both innovative and standard products.

## 1.6 Dissertation Structure

This dissertation is a compilation of four papers supplemented with an introductory part (kappa). This introductory part proceeds as follows.

Chapter 2 begins by laying out the conceptual framework for this research in the first section. The second section briefly reviews the literature on the concepts presented in the conceptual framework in eight subsections: systems thinking, sustainability, information, diffusion of innovations, standardization, digital platform ecosystems, industrialized construction, and design for sustainability.

Chapter 3 concerns the philosophy, reasoning, methodology, approach, and methods employed for conducting this research. It is divided into two sections. The first section explains why critical realism has been adopted as the research philosophy and presents the stages of research in this philosophical framework. The second section describes how critical realism has framed the methodology employed in this research and the methods applied in the four appended papers.

Chapter 4 discusses the main findings of the appended papers in four sections and summarizes the discussion in the fifth section.

Chapter 5 discusses the findings in relation to the research conceptual framework and philosophy and provides reflections on the findings. It includes three sections. The first section is a discussion of the implications for key stakeholders. The second section describes how this dissertation contributes to the field of research. Finally, the third section identifies areas for further research.

# 2 Conceptual Framework and Literature Review

## 2.1 Conceptual Framework

The conceptual framework for this research (Figure 1) has developed through an iterative process of problem identification, contextualization, and conceptualization that will be further discussed in the next chapter. As shown, this framework comprises the interrelated concepts of systems thinking, sustainability, diffusion of innovations, standardization, digital platform ecosystems, industrialized construction, and design for sustainability, with information as the central concept. The following section presents a comprehensive review of the literature on these concepts.

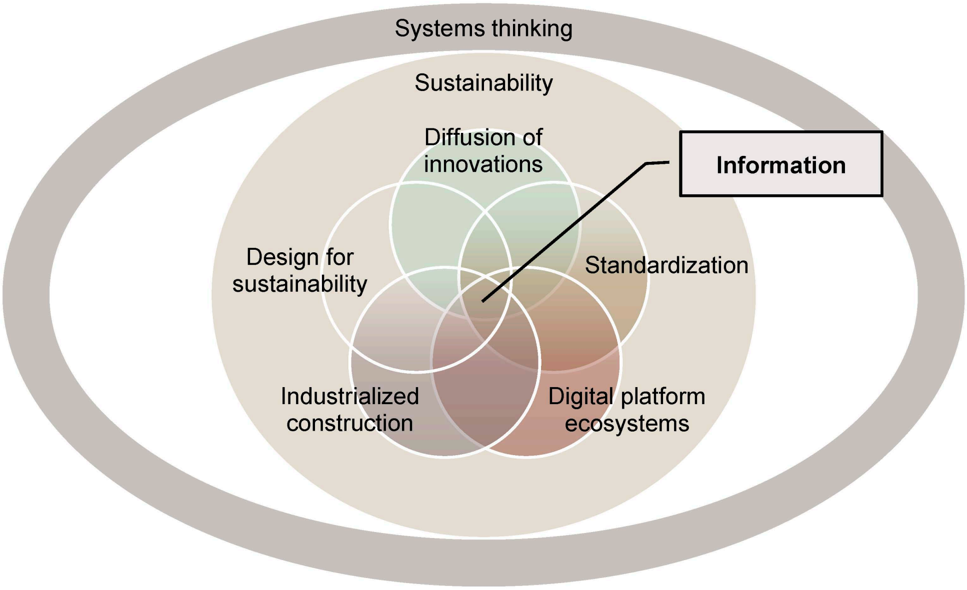


**Figure 1.** The conceptual framework for this research

## 2.2 Literature Review

### 2.2.1 Systems thinking

As illustrated in the conceptual framework (Figure 1), the concept of systems thinking embraces all other concepts in this research. A system is a set of elements interconnected in such a way that they produce their own behavior patterns over time to accomplish a purpose (Meadows, 2008, p. 2). Churchman (1968, p. 29) pointed to five considerations for understanding the meaning of a system.

1) The total system objectives (the performance measures of the entire system)
2) The system's environment (the fixed constraints)
3) The resources of the system
4) The components of the system, their activities, goals, and measures of performance
5) The management of the system

Systems theory provided a sound basis for cybernetics through which scholars such as Wiener (1948), Ashby (1956), and Bateson (1972) studied the transmission of information in circular causality or feedback loops in self-regulating systems (Chowdhury, 2019; Mingers, 2014). Likewise, systems thinking has been long applied in management studies (Chowdhury, 2019; Mingers and White, 2010), specifically in operations research (e.g., Churchman et al., 1957) and organizational psychology (e.g., Katz and Kahn, 1966).

Arnold and Wade (2015) define *systems thinking* as "a set of synergistic analytical skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects". Having systems thinking skills, one can apply logical thinking to gather and analyze information, design and test solutions to problems, and make sensible decisions based on the available information (Arnold and Wade, 2015). This logical way of thinking is the basis for *systems engineering* that is a "methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system" (NASA, 2020). This approach has also been acknowledged and applied in construction projects (Meertins, 2013).

Systems thinking enables us to reclaim our understanding of the entire system and its parts, see the interconnections, ask what-if questions about possible future behaviors, and redesign the system creatively (Meadows, 2008, p. 6). Systems thinking provides a framework for understanding the patterns in interrelations and moving beyond simplistic short-term assumptions about cause and effect (Senge and Fulmer, 1993). Wright and Ceroni (2018) argue that systems thinking provides a holistic design framework for creating change towards sustainable ways of living on this planet. This potential advantage of systems thinking has been investigated in several studies on the sustainable innovation of socio-technical systems (e.g., Chon, 2020; Pereno and Barbero, 2020).

### 2.2.2 Sustainability

The concept of sustainability was developed in the 1960s with emerging new perspectives on socio-economic development (Rostow, 1960; Tilles, 1964) and ecological living (Carson, 1962). In 1987, the United Nations Brundtland Commission defined *sustainable development* as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). Elkington (1997) introduced the *triple bottom line*, a sustainability framework for evaluating firms’ social, environmental, and economic performance. The intention was to call for a systemic change towards eliminating unsustainable sectors (Elkington, 2018).

The creation of sustainable value by firms (Hart and Milstein, 2003) is a concept based on the triple bottom line principle. It involves the creation of mutual benefits for a firm, society, and the environment through collaboration between the firm and stakeholders (Sulkowski et al., 2018). A customer value proposition is a strategic tool used by a firm (Eggert et al., 2018) to describe the benefits customers can gain from its offerings (Osterwalder et al., 2014) as compared to the alternatives offered by its competitors (Lindic and Silva, 2011). Firms can use sustainable value propositions to communicate the value of their sustainable offerings with their customers. A *sustainable value proposition* is “a promise on the economic, environmental, and social benefits that a firm’s offering delivers to customers and society at large, considering both short-term profits and long-term sustainability” (Patala et al., 2016). Sustainable value chains enable firms to benefit from developing sustainable offerings (Nidumolu et al., 2015).

To create sustainable value by their offerings, firms need to communicate the sustainability attributes of their offerings efficiently. For instance, the common sustainability attributes for ventilation products are energy efficiency and indoor environmental performance, including indoor air quality, thermal comfort, and acoustic performance (Sweden Green Building Council, 2020). Manufacturers can communicate the quantified sustainability impacts of their products by reporting the carbon footprint of their products.

The effectiveness of systems thinking in dealing with sustainability problems depends on the quality and flow of information. Although some interconnections in systems are physical (i.e., material and energy) flows, many are information flows going to decision points or action points (Meadows, 2008, p. 14). Information ensures the integrity of a system, and information flow plays a central role in determining how a system operates (Meadows, 2008, p. 14). For example, to evaluate how different design strategies would affect the sustainability performance (e.g., fire resistance) of a building, designers need reliable information on the sustainability attributes of building products (e.g., the combustibility of insulation materials).

### 2.2.3 Information

*Information* is a complicated concept that has been explained in different ways (Bawden and Robinson, 2012, p. 65). For example, it has been defined as “data that has been processed into a meaningful form” and “an assemblage of data in a comprehensible form capable of communication and use” (Cawkell, 2003, p. 244). For Chen and Floridi (2013), *information* means well-formed and meaningful data that must be truthful. Bates (2018) proposes another definition for *information* as “the patterns of organization of matter and energy”. Maksimov and Lebedev (2020) suggest that information manifests itself in a dual nature. While it represents an object, it manifests itself as effectiveness through interacting with other objects and causing change (Maksimov and Lebedev, 2020).

Davis (2000, p. 71) draws distinctions between *data*, *information*, and *knowledge*, suggesting that *data* is “representations of events, people, resources, or conditions” while *information* is “a result of processing data”, and *knowledge* is “information organized and processed to convey understanding, experience, accumulated learning, and expertise”. Davenport and Prusak (1998) define *data* as “a set of discrete, objective facts about events”, and describe *information* as a message that has a sender and a receiver, where its purpose is to shape the way the receiver perceives something. They propose a pragmatic description of *knowledge* as “a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information” (Davenport and Prusak, 1998, p. 5). The ISO 30401:2018 standard on knowledge management systems defines *knowledge* as a “human or organizational asset enabling effective decisions and action in context” (ISO, 2018c). In other words, knowledge is actualized and applied in the mind of knowers, and unlike data and information, it contains judgment (Davenport and Prusak, 1998, p. 5).

Buckland (1991, p. 43) identified three principal uses of the word *information*: (1) *information* as the process of becoming informed, (2) *information* as communicated knowledge, and (3) *information* as things such as data and documents. In Floridi’s (2010, p. 46) view, it is hard to expect that a single concept of *information* would reasonably account for its numerous possible applications. The variety of definitions in ISO standards agrees with Floridi’s (2010) viewpoint. For example, in ISO/IEC 2382:2015 standard on information technology, *information* is defined as “knowledge which reduces or removes uncertainty about the occurrence of a specific event from a given set of possible events", and *data* is defined as "reinterpretable representation of information in a formalized manner suitable for communication, interpretation, or processing" (ISO, 2015b). However, the ISO standard on organization and digitalization of information about buildings and civil engineering works (ISO 19650-1:2018) changes the term *data* to *information* and vice versa (ISO, 2018b). It defines *information* as "reinterpretable representation of data in a formalized manner suitable for communication, interpretation or processing" (ISO, 2018b). The definitions selected for this research are listed in section 1.3.

Figure 2 shows a categorization of information proposed by Floridi (Chen and Floridi, 2013). Information can be *natural information*, which is "well-formed data" such as concentric rings in a cut tree trunk showing its age, or *semantic information*, "well-formed and meaningful data" (Chen and Floridi, 2013). The latter can be analyzed as *instructional information*, defined as "information for something", and *factual information*, defined as "information about something" (Chen and Floridi, 2013). Factual information can be *true information*, "well-formed, meaningful, and truthful data", or *untrue information* (Chen and Floridi, 2013). The *untrue information* is "well-structured and meaningful but not truthful", either intentionally (*disinformation*) or unintentionally (*misinformation*).

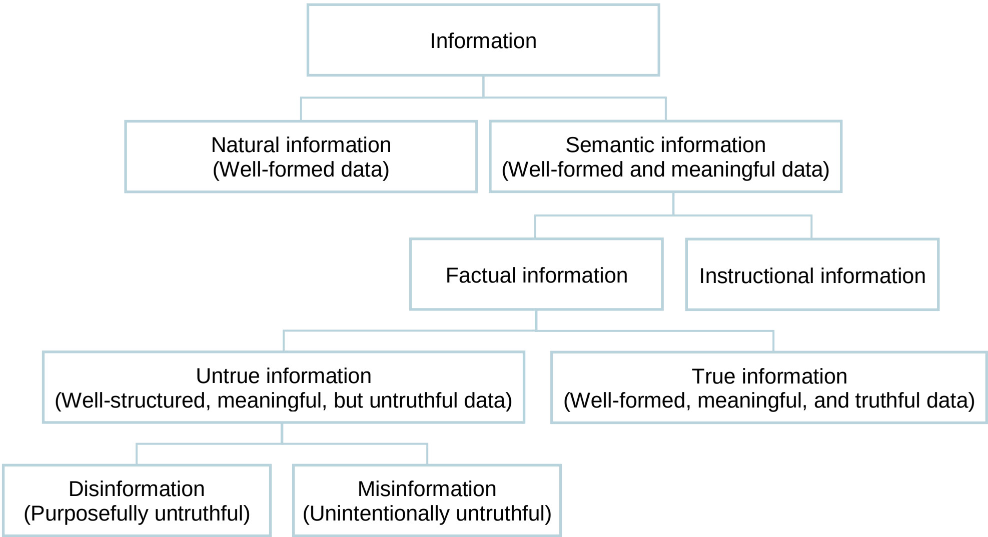


**Figure 2.** A categorization of information (adapted from Chen and Floridi, 2013)

Bates (2018), however, holds the view that all information is *natural information* with an important subclass, named *represented information*. This subclass is *encoded information* or *embodied information* described as follows (Bates, 2018).

- "Encoded information is natural information that has symbolic, linguistic, and/or signal-based patterns of organization."
- "Embodied information is the corporeal expression or manifestation of information previously in encoded form."

Eppler (2006, p. III) suggests that instead of offering the answer and enabling the right decisions, information can cause problems because of its dysfunctional effects, such as confusion. Improving information quality is a sender-based strategy that can be employed to avoid the adverse effects of information (Eppler, 2006, p. III). However, adopting this strategy requires a clear understanding of information quality.

*Information quality* has been defined as the extent to which information "creates value for a user in a particular application" (Talburt, 2010, p. 42), is fit for use by information users (Wang and Strong, 1996), and meets or exceeds their expectations (Kahn et al., 2002). Floridi (2019b, p. 101) argues that perceiving *information quality* as being "fit for purpose" is correct, but this conception requires the differentiation between *P-purpose* and *C-purpose*. The *P-purpose* is the purpose for producing the information, while the *C-purpose* is the purpose for consuming the information (Floridi, 2019b, p. 101). The P-purpose has been addressed in Eppler's (2006, p. 51) definition of *information quality* as "the characteristic of information to meet the functional, technical, cognitive, and aesthetic requirements of information producers, administrators, consumers, and experts".

In Floridi's view, the fundamental quality of information is its truthfulness (Floridi, 2019a, p. 113). Mingers and Standing (2020) suggest that although *truth* and *correctness* seem equivalent in many areas in information systems research and design science, *correctness* is a broader term than *truth*. They argue that the term *correct* can mean "true or conforming to the facts, in accordance with accepted standards, and free from error" (Mingers and Standing, 2020). This argument agrees with Thomson's (2008) notion of two aspects of *correctness*: *internal correctness*, which requires only correctness in carrying out the asserting activity, and *external correctness*, which requires only truth (Thomson, 2008, p. 98). For example, the proposition: "The computer system is down this morning" is internally correct because it is correct English and comprehensible; however, its external correctness depends on whether the computer system is actually down (Mingers and Standing, 2020).

Floridi (2011) proposed the correctness theory of truth to explain how well-formed and meaningful information may become truthful. This theory targets the information users who interact with reality and shape and build it creatively, i.e., system designers (Floridi, 2011). To these users, truth is not merely about experiencing informational artifacts but constructing and handling them and interacting with them successfully (Floridi, 2011). Table 1 presents several dimensions for information quality suggested by Floridi (2019b, p. 108), Talburt (2010, p. 43), and Wang and Strong (1996).

**Table 1.** The categories and dimensions of information quality (Adapted from Floridi, 2019b; Talburt, 2010; Wang and Strong, 1996)

| Information quality categories | Information quality dimensions |
|---|---|
| Intrinsic quality | Accuracy, Objectivity, Reliability of the source |
| Contextual quality | Value-added, Relevancy/Applicability, Timeliness, Completeness |
| Representational quality | Understandability, Consistency, Conciseness |
| Access quality | Accessibility, Access security |

Ashby (1956) pioneered research on digital information technologies. Today, research on information quality is inseparable from studying the quality of digital interfaces that provide information to users. Eppler (2006) has analyzed seven frameworks and 70 criteria for information quality, selected 16 criteria (see Table 2), and proposed a framework for managing information quality in connection with interface quality in knowledge-intensive processes.

**Table 2.** The information quality criteria (Adapted from Eppler, 2006)

| Information quality criterion | Description |
|---|---|
| Comprehensive | The scope of information is adequate (not too much, nor too little). |
| Accurate | The content is precise and close enough to reality. |
| Clear | The content is understandable to the target group. |
| Applicable | The content is useful and can be applied directly. |
| Concise | The content is to the point and free of unnecessary elements. |
| Consistent | The content is free of contradictions or convention breaks. |
| Correct | The content is free of distortion, bias, or error. |
| Current | The content is up-to-date and not obsolete. |
| Convenient | The information provision corresponds to the user's needs. |
| Timely | The information is processed and delivered rapidly without delays. |
| Traceable | The background of the information is visible. |
| Interactive | The information process can be adapted by the user. |
| Accessible | There is a continuous and open way to get to the information. |
| Secure | The information is protected against loss or unauthorized access. |
| Maintainable | The information can be organized and updated continuously. |
| Fast | The infrastructure corresponds to the user's working pace. |

Figure 3 shows Eppler's proposed framework, which has been modified in line with the purpose of this research. The original framework can be found in (Eppler, 2006, p. 68). In this framework, a selection of the information quality criteria (described in Table 2) is categorized into two distinct groups of *content quality* and *media (interface) quality*. The criteria are linked to the four stages of the information use process: identification, evaluation, allocation, and application. These four stages correspond to four information management principles: integration, validation, contextualization, and activation. This approach facilitates the analysis of information quality in connection with interface quality.

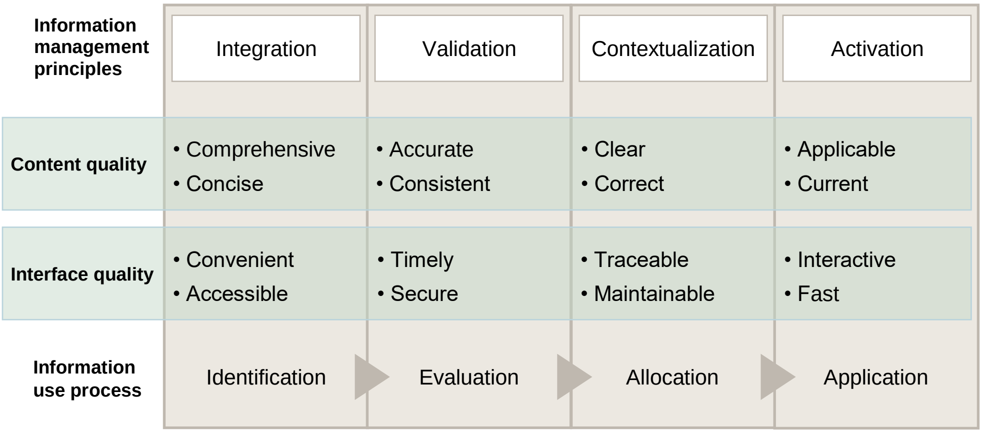


**Figure 3.** A framework for information quality (Adapted from Eppler, 2006)

Adopting a different approach, Peter et al. (2013) distinguish between information system quality and service quality (see Table 3). The identification of service quality highlights the critical role of system providers in ensuring information quality.

**Table 3.** The success variables for an information system (Adapted from Peter et al., 2013)

| Information system success variable | Description | Examples of criteria |
|---|---|---|
| Information quality | Desirable characteristics of the content | Understandability, accuracy, completeness, conciseness, currency, timeliness, relevance, usability |
| System quality | Desirable characteristics of the system | Ease of use, reliability, flexibility, ease of learning |
| Service quality | Quality of the service that users receive from the system provider | Reliability, responsiveness, accuracy, technical competence |

### 2.2.4 Diffusion of innovations

The concept of information and its flow is the basis for the diffusion of innovations. As suggested by the epidemic (Bass, 2004; Rogers, 2003c) theories of innovation and related studies (e.g., Bianchi et al., 2017; Frattini et al., 2014), dissemination of information drives the diffusion of an innovation. Some scholars (e.g., Rice, 2017; Swanson, 1994) refer to *diffusion of innovations* as the adoption process. However, Rogers (2003a, p. 5) defines *diffusion* as "the process in which an innovation is communicated through certain channels over time among members of a social system".

According to Rogers (2003a, p. 6), the diffusion of an innovation is a "special type of communication in which the messages are about a new idea". The most well-known theory of communication is Shannon's mathematical theory of communication (Shannon, 1948). Shannon and Weaver (1949, p. 3) define *communication* as "all of the procedures by which one mind may affect another" that includes all human behavior, and in a broader sense, it includes the procedures through which one mechanism affects another mechanism. In Rogers's view, *communication* is an interactive process "by which participants create and share information with one another in order to reach a mutual understanding" (Rogers, 2003a, p. 5). The success of this process, as Rogers (2003b) suggests, requires communicating three types of knowledge defined as the information on:

- the existence of an innovation (awareness-knowledge)
- how to use an innovation (how-to knowledge)
- theoretical principles behind the functioning of an innovation (principles-knowledge)

The adoption of an innovation cannot occur without awareness-knowledge (Caiazza and Volpe, 2017). To decide on adopting an innovation, potential users need adequate information about how it works. Inadequate how-to knowledge can cause the rejection of an innovation (Rogers, 2003c). An innovation can be adopted without principles-knowledge; however, the absence of this type of information runs the risk of incorrect use and rejection of an adopted innovation (Rogers, 2003c). Notably, principles-knowledge is essential when the information users are professionals, such as heating, ventilation, and air conditioning (HVAC) design and facade design engineers.

From Roger's (2003b) definitions, we can infer that he has used the terms *knowledge* and *information* interchangeably. Although the diffusion of an innovation begins with communicating the information about its existence, its success depends on the user's perception of the characteristics described in Table 4 (Rogers, 2003a). Information shapes the receiver's perception of something (Davenport and Prusak, 1998, p. 3); thus, the success of the diffusion of an innovation depends on the quality and flow of information about its characteristics (see Table 4).

**Table 4.** The perceived characteristics of an innovation influencing its adoption (Adapted from Rogers, 2003)

| Characteristic | Description |
|---|---|
| **Relative advantage** | the degree to which an innovation is perceived as better than the idea it supersedes |
| **Compatibility** | the degree to which an innovation is perceived as being consistent with the existing values |
| **Complexity** | the degree to which an innovation is perceived as difficult to understand and use |
| **Trialability** | the degree to which the performance of an innovation can be experimented |
| **Observability** | the degree to which the results of an innovation are visible to others |

Typically, the diffusion of innovations involves uncertainty (Rogers, 2003a, p. 14) because the potential adopters are commonly uncertain about the improved features (Zsifkovits and Günther, 2015) or the future performance of a product (Engström and Hedgren, 2012). The diversity of sources and types of information regarding an innovation enables its diffusion by reducing the uncertainty about its characteristics, use, and effects (Rice, 2017).

A significant source of building product information is BIM object libraries supplying product information in the form of BIM objects (Gao et al., 2017; Pasini et al., 2017). A BIM object must contain detailed information on the identity, dimensions, appearance, and performance of a product (BSI, 2018). We can infer that a perfect BIM object representing an innovative product can foster its diffusion by enhancing trialability and observability. This requires careful attention to the quality of BIM objects and usability of BIM object library websites as the interfaces that provide BIM objects.

### 2.2.5 Standardization

Standardization can support the diffusion of innovations through facilitating the exchange of information (Blind, 2017; Featherston et al., 2016; Swann, 2010), enabling more effective communication (Blind and Gauch, 2009; Egyedi and Ortt, 2017; Tassey, 2015), and establishing credibility for an innovation (Viardot, 2017). Previous studies have suggested several methods for classifying the functions of standards. Examples are quality and performance (Swann, 2010), measurement and characterization (Featherston et al., 2016; Ho and O'Sullivan, 2015), and compatibility (Egyedi and Ortt, 2017; Swann, 2010). Table 1 in Paper II provides a complete list of the functions identified in previous research.

It is widely accepted that standards on test and performance measurements are necessary for quality assurance in manufacturing processes (Tassey, 2015, 2000).

In particular, these standards are required for innovative products because of the uncertainties mentioned in the previous section. Standards for test and measurement (Egyedi and Ortt, 2017) and quality (Blind, 2013; Blind et al., 2018) can reduce uncertainties and facilitate the diffusion of innovations. Since uncertainty increases transaction costs (Wolter and Veloso, 2008), standards for quality reduce transaction costs by reducing uncertainties over the quality of the product (Blind, 2013; Blind et al., 2018; Tassey, 2015).

Standards on information and terminology increase communication efficiency during innovation processes (Blind and Gauch, 2009). In particular, standardizing product information enhances communication and the exchange of information between various stakeholders (Ho and O'Sullivan, 2015) and reduces information costs (Blind and Gauch, 2009). Moreover, standardized product information facilitates the comparison between products (Egyedi and Ortt, 2017), reduces transaction costs, and increases market penetration (Tassey, 2015). Ho and O'Sullivan (2015) suggest that standardized terminology and reference units assist standards committees of new technologies using a common language in developing and publishing-related standards. In addition, supplying standardized information about the sustainability attributes of products can encourage purchasing choices that are more informed to support sustainability (Cho et al., 2018). The European Union has aimed to provide a harmonized technical language to assess the performance of construction products by issuing the construction products directive in 1989 and replacing it with the construction products regulation in 2011 (European Commission, 2021).

### 2.2.6 Digital platform ecosystems

The platform business model is an effective strategy for delivering innovations (Kim, 2016). Platforms enable external producers and consumers to create value in an interactive ecosystem (Parker et al., 2017c). A *digital platform* is defined as "a set of digital resources—including services and content—that enable value-creating interactions between external producers and consumers" (Constantinides et al., 2018). The design logic of the platform business model is open networks (Fehrer et al., 2018). In a digital platform ecosystem, the network effect increases users' interactions (Eisenmann et al., 2011) and increases the value of the offerings (Hagiu and Altman, 2017). The term *network effect* is referred to as the impact of the number of users (Shapiro and Varian, 1999, p. 174) on the value created for a user in a digital platform ecosystem (Parker et al., 2017a, p. 17).

Digital platforms have four types of actors: the owners of platforms who govern the platform and control the intellectual property, the providers of the interface, the producers of the offerings, and the consumers of the offerings (Van Alstyne et al., 2016). The owner and the service provider could be the same company as the companies studied in Paper III. Every platform has a core interaction that is the mission of that platform for creating value. The core interaction is formed by determining three key elements: the participants, the value unit, and the filter (i.e., the interface) (Parker et al., 2017b).

BIM object libraries are digital platform ecosystems for the exchange of information on building products. The key elements of BIM object library platforms are building product manufacturers and architecture, engineering, and construction (AEC) professionals, BIM objects, and the BIM object library website (Bahrami et al., 2019). Some of the well-known BIM object library platforms are BIMobject (BIMobject, 2021), NBS BIM library (NBS, 2021), BIMstore (BIMstore, 2021), and MagiCAD cloud (MagiCAD, 2021). A shortcoming in the existing BIM object libraries is that they use different terminologies (Chen et al., 2017) and provide different types of information for similar products made by different manufacturers (Gao et al., 2017; Pasini et al., 2017). Anumba et al. (2008) argued that common reasons for dissimilarities between methods of representing information are differences in data types, value differences, semantic differences, and missing values. An attempt to deal with these problems is the BSI Kitemark for BIM objects, third-party certification for validating the accuracy and functionality of BIM objects (BSI, 2017).

The quality of digital information and the quality of the interface that provides the information are mutually dependent. The quality of an interface can be assessed by usability evaluations that are common in software engineering. Various approaches to software usability evaluation can be found in (Doesburg et al., 2017; Dumas and Loring, 2008; Speicher et al., 2015; Tarkkanen et al., 2015; Vilbergsdottir et al., 2014). The ISO/IEC 25062 standard defines *usability* as “the extent to which a product can be used by specified users to achieve specific goals with effectiveness, efficiency and satisfaction in a specified context of use” (ISO, 2006). McGlinn et al. (2017) evaluated software usability for improving energy efficiency in buildings by investigating whether the software content was accessible and understandable for facility managers.

In manufacturing, product life cycle management (PLM) is a management system for the integrated management of product-related information and processes throughout the entire life cycle of a product (Schuh et al., 2008). Although PLM has been established in manufacturing for nearly two decades (see Christman, 2002), a life cycle approach has not been adopted in developing BIM objects of building products. In other words, a BIM object of a product does not contain information about the entire life cycle of the product.

In contrast, a digital twin is a dynamic virtual representation of a physical object or system across its life cycle (Bolton et al., 2018). A digital twin can represent a product, an asset, a process, a system, or a network of systems (Arup, 2019). It uses real-time data to enable understanding, learning, reasoning (Bolton et al., 2018), and performing real-time optimization (Söderberg et al., 2017). Utilizing digital twins in manufacturing aims to reduce costs, time, and most importantly, harm to users by identifying the manufacturability and failure modes before producing a physical system (Grieves and Vickers, 2017). The application of digital twins has been studied in industrialized prefabrication of building modules (e.g., Gerhard et al., 2020), evaluation of building control strategies (e.g., Nytsch-geusen et al., 2019), and facility operation and management (e.g., Arnold and Teicholz, 2021; Jaribion et al., 2020). Zhou et al. (2020) proposed a digital process platform for future construction sites and the integration of digital twins into such platforms. However, Bosch-Sijtsema et al. (2021) suggest that the variation in perceptions and definitions of digital twins might affect the information on the usage of this technology in the AEC industry. Digital twins that could revolutionize design processes are predictive digital twins, which are currently theoretical. Kapteyn et al. (2021) propose a predictive digital twin that uses dynamic data-driven learning to produce a graphical model of a physical object.

### 2.2.7 Industrialized construction

Industrialized construction involves modern methods of construction (Spisakova and Kozlovska, 2020) and the concepts of prefabrication, standardization, automation, and sustainability (Li et al., 2020; Zabihi et al., 2013). Traditional construction systems have been recognized as inefficient systems (Dubois et al., 2019) with limited incentives and possibilities for systematic production (Andersson and Lessing, 2020). On the other hand, industrialized construction creates opportunities for product orientation (Hall et al., 2020) and systematic production processes that facilitate continuous improvement in the design, manufacturing, and assembly of building modules (Andersson and Lessing, 2017). Moreover, industrialized construction facilitates information management owing to standardized procurement processes (Jansson, 2016) and work procedures (Eriksson et al., 2019). The application of industrialized construction in residential building projects, known as industrialized house-building (e.g., Jansson et al., 2018; Lessing et al., 2015), includes design and construction processes ranging from high levels of constraints to full customizations applying either on-site or off-site prefabrication (Jansson et al., 2018). Kedir and Hall (2021) suggest that industrialized housing construction can increase resource efficiency through a combination of approaches, including standardization and digitalization.

Prefabrication and modularization are essential principles in industrialized construction (Li et al., 2020). Modularization is a prominent approach to the design of complex systems in systems engineering (Sinha et al., 2020) and manufacturing (Ma and Kremer, 2016). Baldwin and Clark (1997) recognized modularity as a solution to growing complexity and defined it as “building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole”. A product structure is modularized according to objectives, such as improving assembly (Windheim, 2020, p. 8). Prefabricated building units include volumetric modules such as bathrooms (Jansson et al., 2018), and panelized modules such as interior walls (Said et al., 2017), facades (Montali et al., 2018; Said et al., 2017), and floors (Jansson et al., 2018).

Modularization advances the construction industry by transferring a portion of on-site work to fabrication shops (O'Connor et al., 2014), which extends the manufacturing sector's influence in the construction industry. Modular construction can enhance construction productivity by utilizing manufacturing principles (Yang et al., 2020). This decomposition of the target system into interconnected modules during product design (Sinha et al., 2020) can improve product life cycle sustainability (Ma and Kremer, 2016). However, problems such as lack of design codes and standards (Enshassi et al., 2019), supply chain complexity and uncertainty (O'Connor et al., 2014), and logistics obstacles, particularly in high-density cities, can limit the advantages of modular construction (Yang et al., 2020). Furthermore, Hussamadin et al. (2020) suggest that unstructured flow of information has caused fragmentation between off-site manufacturing and on-site construction in industrialized house-building.

The effective use of modularization requires changes in engineering, procurement, and construction processes (O'Connor et al., 2014) as well as real-time information and standardized information flow (Hussamadin et al., 2020). Table 5 lists the determining factors in the success of modular construction (Wuni and Shen, 2020), which are linked to the flow of information.

**Table 5.** The success factors for modular construction projects (Adapted from Wuni and Shen, 2020)

| Project stage | Success factor |
|---|---|
| **Planning and procurement** | • Intensive initial research on modularization<br>• Stakeholders' knowledge of modular construction projects<br>• Early advice from modular design professionals and experts<br>• Early identification and confirmation of critical decisions by all parties involved<br>• Early and precise definition of technical scope, planning, and budget<br>• Clearly defined goals and responsibilities<br>• Improved supply chain coordination and management<br>• Availability of personnel with required technical skills and experience<br>• Early and effective use of information and communication technology |
| **Design and manufacturing** | • Fabricator's resources and experience in modular design and production<br>• Early consideration of module limitations (e.g., logistics)<br>• Appropriate modular design codes and regulations |
| **Implementation** | • Effective collaboration and exchange of information among all parties<br>• Effective coordination between off-site and on-site construction activities |
| **Post-project review** | • Standardization, optimization, and benchmarking of best practices<br>• Systematic measurement of performance<br>• Utilization of the lessons learned, and continuous improvement and learning |

### 2.2.8 Design for sustainability

*Design* has been recognized as a co-evolution of problem and solution (Dorst, 2019a; Maher and Poon, 1996), during which designers investigate the problem and design the solution (Pressman, 2018, p. 85). Maher and Poon (1996) proposed a model for problem-design exploration, which they defined as a phenomenon in design where the problem interacts and evolves with the solution. In this model, the problem space and the design (solution) space are two distinct search spaces that interact over time (Maher and Poon, 1996).

This model has been modified and presented in (Maher and Tang, 2003) as a model for co-evolutionary design. Figure 4 illustrates a combination of the two presentations of the model. The horizontal arrows show the evolution in the two spaces, and the diagonal arrows show the interactions between the spaces. This co-evolutionary process involves iterative explorations in the problem/requirements space and the solution/design space, while the interactions between the two spaces may add new variables to the process (Maher and Tang, 2003). In the axiomatic design approach (Farid and Suh, 2016), these two spaces are the functional domain that encloses the functional requirements and the physical domain that includes the design parameters. Dorst (2019a) argues that capacity building for co-evolution and the ability to think between the problem space and the solution space is necessary in all professional fields.

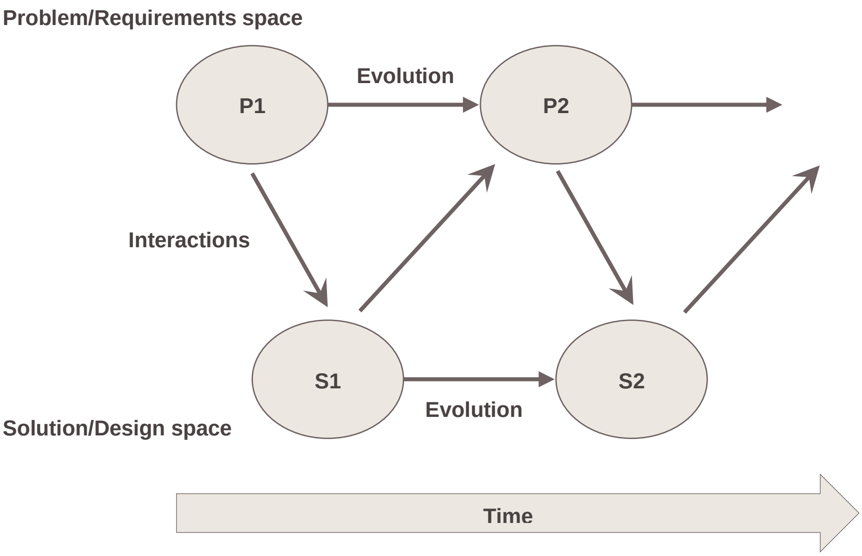


**Figure 4.** Problem-Design exploration model (Adapted from Maher and Poon, 1996; Maher and Tang, 2003)

Kroll and Koskela (2015) proposed a model for the parameter analysis process in design, which involves iterative moves between the concept space and the configuration space through applying parameter identification, creative synthesis, and evaluation (see Figure 5). We can see similarities between this model and the model shown in Figure 4, but different terms have been used to refer to the spaces and processes. The design approach and the context of design govern the activities during a design process. Preece et al. (2015, p. 15) identify four basic activities for interaction design: (1) discovering requirements; (2) designing alternatives that meet the requirements; (3) prototyping the alternative designs; and (4) evaluating the product.

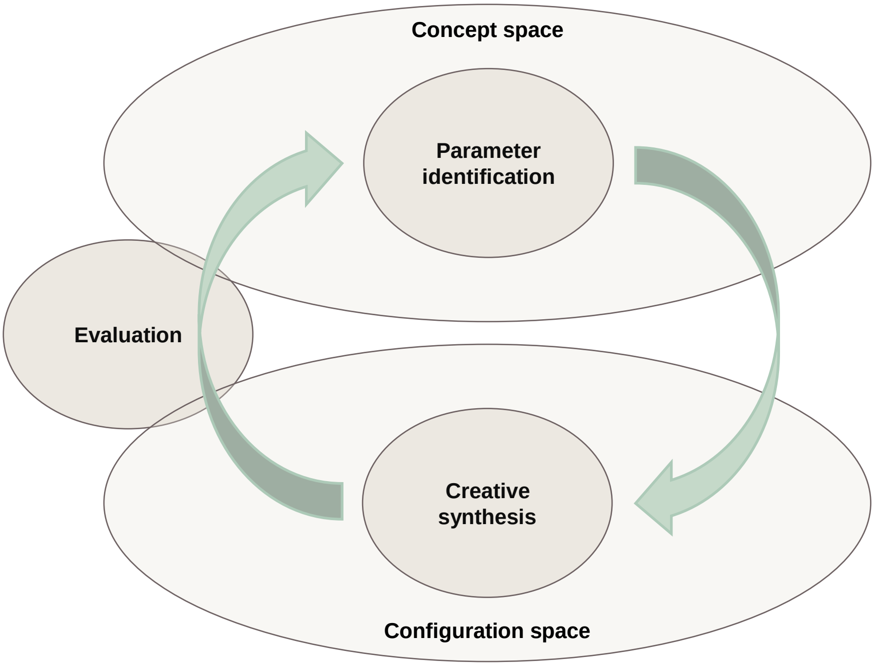


**Figure 5.** The parameter analysis process in design (Adapted from Kroll and Koskela, 2015)

Design for sustainability has been recognized as design, education, and research contributing to sustainable development (Vezzoli et al., 2018). Since the 1990s, the design of products with low environmental impacts has received exceptional attention (Vezzoli et al., 2018). It has been applied in design approaches such as green design, eco-design, and product life cycle design (Ceschin and Gaziulusoy, 2016; Vezzoli et al., 2018).

Table 6 lists the indicators that can be used to assess the sustainability performance of building components.

**Table 6.** The sustainability performance indicators for building components

| Indicator | Adapted from: |
|---|---|
| • Indoor air quality<br>• Comfort (thermal, acoustic, visual)<br>• Energy efficiency<br>• Material efficiency<br>• Water efficiency | (Bragança et al., 2010; Häkkinen, 2012; Sweden Green Building Council, 2020) |
| • Structural safety<br>• Fire safety<br>• Electrical safety | (Ho et al., 2008) |
| • Water safety<br>• Material safety | (Sweden Green Building Council, 2020) |
| • Greenhouse gas emissions<br>• Waste generation<br>• Maintenace and replacement | (Boverket, 2020; Häkkinen, 2012) |
| • Security | (Ettouney, 2015; Häkkinen, 2012) |

However, Ceschin and Gaziulusoy (2016) reviewed 11 approaches to design for sustainability and concluded that although some of these approaches include the entire life cycle of products, limited attention has been given to the human-related aspects. Notable examples are energy-efficient design strategies, including combustible insulation materials and photovoltaic panels, which have led to unacceptable consequences of facade fires (Meacham and McNamee, 2020).

The Grenfell Tower fire is a tragic example of fatal facade fires fueled by combustible insulation materials. More details on how design and construction defects led to the catastrophic consequences of that incident are provided in Paper IV. Furthermore, Paper IV describes the Bolton Cube fire and visualizes the increasing number of facade fires worldwide to emphasize that the problems in facade design are not limited to the Grenfell Tower case, and such problems can still create serious hazards for building users. This shows the need for systems thinking in building design for sustainability to identify the safety risks and the negative environmental and economic impacts of the strategies that have been considered green or sustainable.

*Human-centered design* has been defined as “a group of methods and principles aimed at supporting the design of useful, usable, pleasurable, and meaningful products or services for people” (Van der Bijl-Brouwer and Dorst, 2017). Hanington (2018) suggests that human-centered design can be sustainable by paying balanced respect to people, the planet, and profit. Gasson (2003) distinguishes between user-centered and human-centered approaches to design, arguing that user-centered design focuses on technology and considers humans as technology users, while human-centered design aims to create proper changes to a human-activity system supported by technology. Managing multiple stakeholders, integrating multiple fields of professional knowledge, and dealing with design situations with no clear user have been recognized as considerable challenges in designing complex systems (Dorst, 2019b). Research has shown that building design faces the same challenges (O'Connor and Koo, 2021; O'Connor and Koo, 2020).

Although a user-centered approach is appropriate for architectural design, satisfying the needs of building users is an enormous challenge for architects because of conflicting demands from various stakeholders (Krukar et al., 2016). Moreover, future building users and space uses cannot be specified during design and permitting processes (O'Brien et al., 2020a), while building codes commonly classify buildings based on the occupancy types, such as residential and commercial. O'Brien et al. (2020b) mention that despite the significant impact of occupancy and occupant behavior on building performance, there is a lack of knowledge, standards, and tools to support occupant-centric building design. Also, collaboration problems occur in design teams because of distinct design approaches adopted by architects and engineers (e.g., Marchesi and Matt, 2016).

Benyon (2019, p. 31) draws our attention to the fact that the designer's conception of the system they have designed might differ from what the system does in reality. For large systems designed by various designers (such as buildings), no single designer could have an unrestricted view of the entire system performance (Benyon, 2019, p. 31). Vanasupa et al. (2010) argued that design leads to unsustainable consequences if the designers' mental models and design processes are detached from the more extensive system in which the design is embedded.

Unlike the product design in manufacturing and software engineering, the final product cannot be prototyped and tested before the final design decision. Therefore, simulations and modeling are used to evaluate design alternatives. Meadows (2008, p. 45) suggested that asking three questions would help us evaluate how good a model is as a representation of reality.

1) Would the driving factors act this way?
2) If they did, would the system react this way?
3) What is influencing the driving factors?

The answer to the first question is a prediction about the inherently uncertain future and cannot be proved until the future actually happens (Meadows, 2008, p. 45). The second question is about the ability of the model to capture the inherent dynamics of the system (Meadows, 2008, p. 47). Answering the third question requires identifying the system boundaries and the factors adjusting the inflows and outflows (Meadows, 2008, p. 48).

Morell (2018) argues that a systematic interaction between data collection and model revision over the entire design evaluation process can improve the process and prevent unintended design consequences. The concept of predictive digital twins, proposed by Kapteyn et al. (2021), aims to narrow the gap between a physical object and its graphical model by dynamic data-driven learning.

Researchers in building design have explored common design approaches and principles in other fields. For example, De Souza (2012) studied the concept of design thinking used by building designers and thermal simulation tool users. This concept has also been applied in research on performance-based building design (e.g., Rezaee et al., 2019). Furthermore, Krukar et al. (2016) suggest that architects use human-computer interaction (HCI) principles to apply or improve a user-centric approach in their designs.

The application of design approaches based on systems engineering has been widely studied in building design. For instance, de Wilde (2018) studied applying the requirements engineering approach to develop software systems for building performance analysis. Marchesi et al. (2016) applied an axiomatic design approach, developed by Nam P. Suh (Farid and Suh, 2016), in two case studies on prefabricated housing projects. Another example is an approach to refugee shelter design by integrating the quality function deployment (QFD) method, developed by Mitsubishi Heavy Industries and adopted by Toyota, with the axiomatic design developed by Nam P. Suh (Gilbert III et al., 2016).

The concept of DfMA is a combination of *design for manufacture* and *design for assembly* (Boothroyd et al., 2002). The former means the design for ease of manufacturing the individual parts of a product or assembly, while the latter means the design for ease of joining of parts to form the completed product (Boothroyd et al., 2002). In 1993, Bridgewater proposed applying design for automation in construction through an integrated design and construction process involving off-site manufacturing and prefabrication and on-site automation (Bridgewater, 1993). A growing trend in industrialized construction has led to a renewed interest in the application of DfMA in construction projects. Recent studies suggest that applying production-based design concepts such as DfMA are required to increase industrialized construction efficiency (Ramaji et al., 2017).

The application of DfMA can reduce planning and construction work, logistics, and associated costs in high-rise building (Banks et al., 2018) and facade system (Chen and Lu, 2018) projects. Nguyen et al. (2020) suggest that limited accuracy of lifting cranes during the installation of prefabricated facades might create misalignments that cause fire spread. Such problems could be addressed by adopting a DfMA approach because it has been proposed to prevent the assembly and installation problems early in the design stage of a product life cycle (Gao et al., 2020; Lu et al., 2020).

# 3 Research Philosophy and Methodology

*Research philosophy* is defined as “a system of beliefs and assumptions about the development of knowledge” (Saunders et al., 2019, p. 130). Researchers make various types of assumptions at every stage in their research (Burrell and Morgan, 1985, p. 3), including ontological, epistemological, and axiological assumptions (Saunders et al., 2019, p. 130). The ontological assumptions are about the realities researchers encounter in their research (Saunders et al., 2019, p. 133) and underpin a researcher’s philosophical beliefs about what constitutes social reality (Yin, 2016, p. 338). The epistemological assumptions are about human knowledge (Saunders et al., 2019, p. 133). These assumptions uphold a researcher’s philosophical beliefs about the nature of knowledge and how it is created or derived (Yin, 2016, p. 335). The axiological assumptions relate to how a researcher’s values influence the research process (Saunders et al., 2019, p. 134).

The researchers’ assumptions determine how they understand their research questions, use methods, and interpret their findings (Crotty, 1998). A consistent set of assumptions will establish a credible research philosophy underlying a researcher’s choice of research methodology, strategy, and data collection and analysis techniques (Saunders et al., 2019, p. 130). Figure 6 shows the interrelations between researchers’ assumptions and beliefs, research philosophy, and research design.

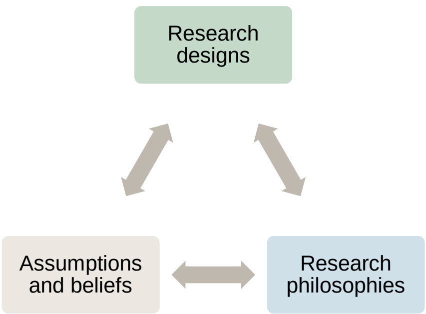


**Figure 6.** The interactions among the research elements (After Saunders et al., 2019)

The philosophy, reasoning, methodology, approach, and method of this research are presented in Figure 7. The model is modified from the research onion suggested by Saunders et al. (2019, p. 130) to serve the purpose of this dissertation. As can be seen, influenced by critical realism philosophy, this research applies abductive reasoning through a qualitative methodology. The research approach is multiple-case study, and the data has been collected and analyzed qualitatively.

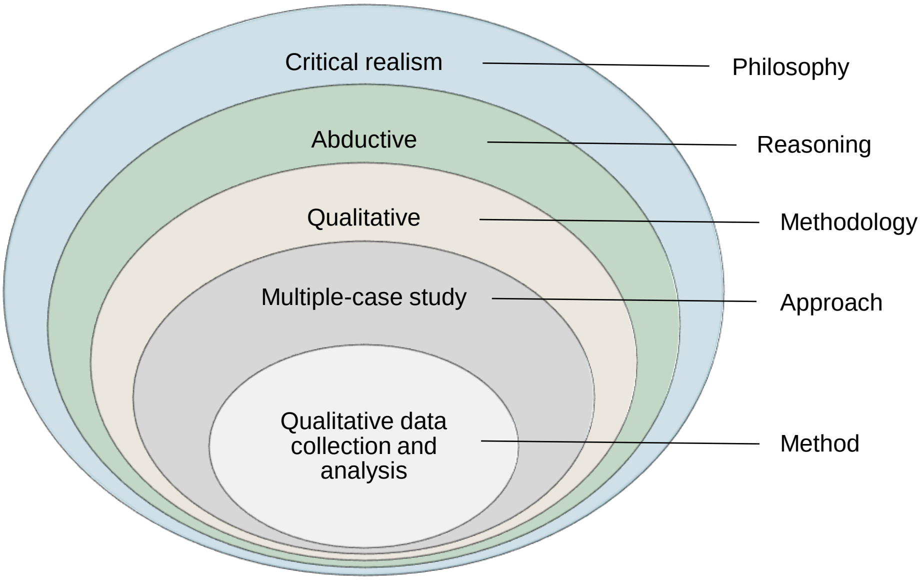


**Figure 7.** The philosophy, methodology, and approach in this research (After Saunders et al., 2019)

## 3.1 Critical Realism Philosophy and Reasoning

This research has been conducted in the philosophical framework of critical realism popularized by Roy Bhaskar (2014a). Critical realism is an appropriate scientific philosophy to approach sustainability problems (Bhaskar, 2014b) through interdisciplinarity (Bhaskar et al., 2010) and create positive changes in our world (Bhaskar et al., 2018). An interdisciplinary perspective is required to address sustainability problems and achieve adequate understanding in research that has a single area of interest (Danermark, 2019).

Critical realism strongly promotes the existence of a reality independent of our knowledge of it (i.e., ontological realism) while accepting that our knowledge of that reality is locally situated and provisional (i.e., epistemological relativism) (Mingers, 2011, p. 73). Instead of prediction (manipulation and control), justification, and apology, critical realism focuses on discovery, understanding, and transformative change (Bhaskar, 2014a). This philosophy of science has gained popularity in social scientific research (Fletcher, 2017) and studies on information systems (Mingers, 2011). Applied critical realism (Bhaskar, 2014a) aims to unitize theory and practice through a philosophy we can act on (Bhaskar, 2014b). It has been applied in empirical research on organizations (Edwards et al., 2014) as well as BIM concerning the diffusion of innovations (e.g., Lindgren, 2018; Poirier et al., 2016) and standardization (e.g., Hooper, 2015).

From a critical realist perspective, reality is stratified into three layers (domains), and scientific research aims to discover the nature of things that are not evident to our experience (Bhaskar et al., 2018). As shown in Figure 8, these domains are the real, the actual, and the empirical (Bhaskar et al., 2010). The domain of the real includes not only the actual and empirical domains but also non-actualized possibilities; the domain of the actual includes the empirical domain as well as things and events that exist or occur but have not been experienced by human beings (Bhaskar et al., 2010). The actual is only one manifestation of the real, while other different manifestations are possible (Bhaskar et al., 2018). The focus in critical realist research is on the structures and mechanisms (i.e., the domain of the real) rather than regularities and patterns of events (i.e., the domains of the actual and empirical) (Bhaskar et al., 2018).

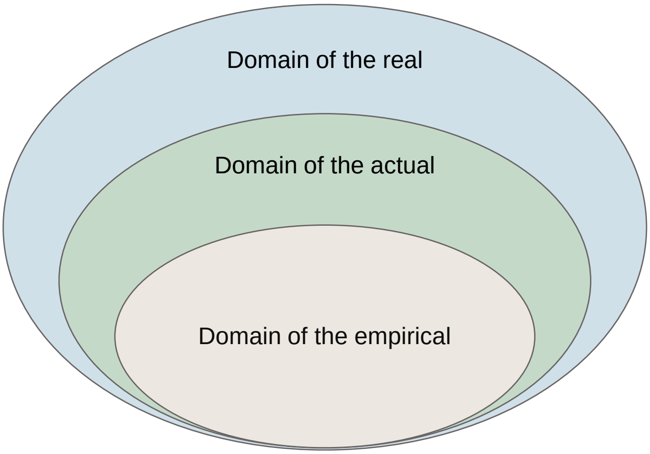


**Figure 8.** The domains of reality in critical realism

In critical realist research, holistic causality hypothesizes internal relations between the elements of a complex system, which means what happens to an element affects the other elements (Bhaskar, 2014a). For that reason, the elements cannot be dealt with individually for explanatory and research purposes (Bhaskar, 2014a). Instead, researchers influenced by critical realism decompose a complex phenomenon into the structures and mechanisms affecting the phenomenon while still considering its complexity (Danermark, 2019). This view of causation is strongly connected to the concept of systems thinking (Mingers, 2014, p. 4). Although systems theory and systems thinking are not mentioned explicitly in Bhaskar's works, critical realism is inherently systemic (Mingers, 2014, 2006).

The three main types of scientific reasoning are *deductive*, *inductive*, and *abductive reasoning*. The *deductive reasoning* process starts with reasons and seeks consequences (Magnani, 2009, p. 10). It involves moving from theory to data (Saunders et al., 2019, p. 155) and relies on a strict logic of theory-testing and falsifying hypotheses (Bell et al., 2019, p. 24). *Inductive reasoning* is a process of the generalization of knowledge (Magnani, 2009, p. 13) through moving from data to theory (Saunders et al., 2019 p. 155).

The term *abductive reasoning* was coined by philosopher Charles Sanders Peirce (Weick, 2005) as "inferential creative process of generating a new hypothesis" (Magnani, 2009, p. 8). *Abductive reasoning* is also known as "inference to the best explanation" (Douven, 2017; Lipton, 2000). This reasoning process is the central logic of scientific discovery in critical realist research (Bhaskar, 2014a) and involves both deduction and induction (Bhaskar, 2014a; Saunders et al., 2019, p. 155).

Thagard and Shelley (1997) define *abductive reasoning* as "reasoning in which explanatory hypotheses are formed and evaluated". It is usually considered as reasoning from specific observations to their explanations (Magnani, 2009, p. 29). During this process, the abductive logic of discovery and the inductive logic of evaluation are combined with the deductive logic of consistency (Nesher, 2001). Deduction can draw a prediction that can be tested by induction (Nesher, 2001). Induction is used to reduce the uncertainty of established hypotheses by comparing their consequences with observed data (Magnani, 2009, p. 465). Dunne and Dougherty (2016) describe the process of abductive reasoning as follows.

> "The process of abductive reasoning moves from surprising insights to formulate, evaluate, and reframe hypotheses by cycling through three social mechanisms: using clues to imagine a configuration of interactions; elaborating and narrowing around the interactions in the imagined configuration to examine alternatives and build on intermediary models; and iteratively integrating across disciplinary boundaries to reframe the configuration of interactions."

In critical realist research, abduction entails interpreting and redescribing the components and aspects of phenomena and examining various theoretical frameworks (Danermark et al., 2019, p. 130) to recontextualize and explain a causal mechanism or process (Bhaskar, 2014a). It involves combining observations (from the observational data or interviews) with the theory (identified in the literature review) to provide the most plausible explanation for the mechanisms that caused the events (O'Mahoney and Vincent, 2014, p. 17).

Another distinct logic of scientific discovery in critical realist research is retroduction, which is developing a model of a mechanism (Bhaskar, 2014a) by identifying patterns in different contexts over periods and asking what-if questions to identify hidden causal mechanisms (O'Mahoney and Vincent, 2014, p. 17). Placing the objects of study in new contexts enables original knowledge about them to be developed (Danermark et al., 2019, p. 130).

Figure 9 illustrates the model for conducting this research through seven main stages. This model has been developed by modifying and integrating two models described by Bhaskar (2014a) into the stages proposed by Danermark et al. (2019, p. 130) for critical realist explanatory research. In addition, an analysis of findings across the case studies (O'Leary, 2016) has been included as the sixth stage to synthesize findings from the four case studies.

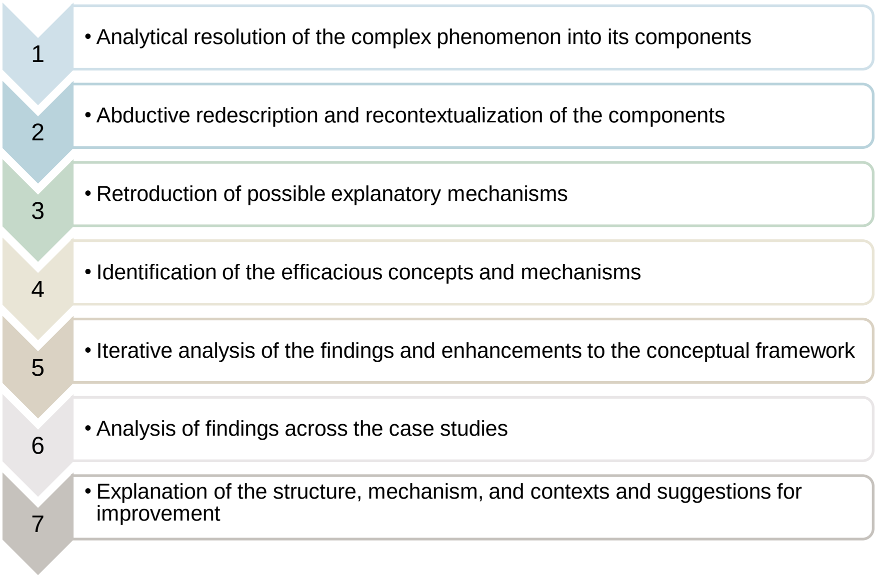


**Figure 9.** The stages of this research in the framework of critical realism (After Bhaskar, 2014a; Danermark et al., 2019)

## 3.2 Research Methodology

Qualitative research is a popular and fruitful way of conducting research that provides insights into existing or emerging concepts (Yin, 2016, p. 6). Qualitative researchers intend to describe what is observable and locate it in the larger context that provides the meanings of action and insight about its purposes, consequences, and functions (Silbey, 2021). This is a valuable methodology in management research (Singh, 2015) on account of enabling researchers to use various sources of information (Yin, 2016, p. 9). In critical realist research, using different sources of information facilitates the identification of tendencies or demi-regularities and establishes the basis for retroductive reasoning through inferring patterns and causation (Kessler and Bach, 2014, p. 171). Therefore, critical realism is undoubtedly in favor of qualitative research (Brown and Roberts, 2014, p. 304), while the approach to research methods is highly flexible and adaptive (Ackroyd and Karlsson, 2014, p. 22).

A common approach in qualitative research is the case study approach (Creswell and Poth, 2018, p. 9), recognized as an empirical approach to the in-depth study of a contemporary phenomenon within its real-world context (Yin, 2018, p. 14). Conducting case studies is compelling in critical realist research because the in-depth analysis enables researchers to understand the continually deepening layers of reality throughout their search for generative mechanisms (Kessler and Bach, 2014). From a critical realist perspective, social phenomena occur in open systems characterized by complexity and emergence (Bhaskar, 2014a). Therefore, the researchers must relate a mechanism to explanatory structures (as in natural science) as well as its context or field of operation (Bhaskar, 2014a).

A general criticism of qualitative research is that this type of research cannot provide a solid basis for generalization (Brown and Roberts, 2014, p. 304; Bell et al., 2019, p. 374). On the other hand, it is claimed that the focus on generative mechanisms in critical realist research enables researchers to make generalizations based on the findings of (multiple) qualitative case studies (Brown and Roberts, 2014, p. 306). As each case study examines the same mechanisms in a different context, a synthesis of all case studies allows generalization about the generative mechanisms and their operations in different contexts (Brown and Roberts, 2014, p. 306). For that reason, a multiple-case study has been selected as a proper approach to conduct this research.

A fundamental component of a case study design is defining the case, which should be a real-world phenomenon with some concrete manifestation (Yin, 2018, p. 27). In critical realist research, researchers must think of a quartet composed of structure, mechanism, outcome, and context (Bhaskar, 2014a). In this research, this quartet had to be thought about beforehand to define the case studies. Therefore, the quartet presented in Figure 10 was established as the basis for case study design. As shown, the construction industry is determined as the structure in which the mechanism of creating and providing information is explored. This exploration focuses on the sustainability impacts of products as the outcome of this mechanism. The contexts are operative processes or the desired sustainable processes, which are influenced by creating and providing product information. Table 7 lists the sustainability performance indicators and the operative processes in each case study.

Researchers influenced by critical realism should continually think of further concepts and information that provide valuable insight into the mechanisms under study (Ackroyd and Karlsson, 2014, p. 22). Table 8 shows how the conceptual framework for this research has been enriched throughout four sequential case studies presented in Papers I to IV.

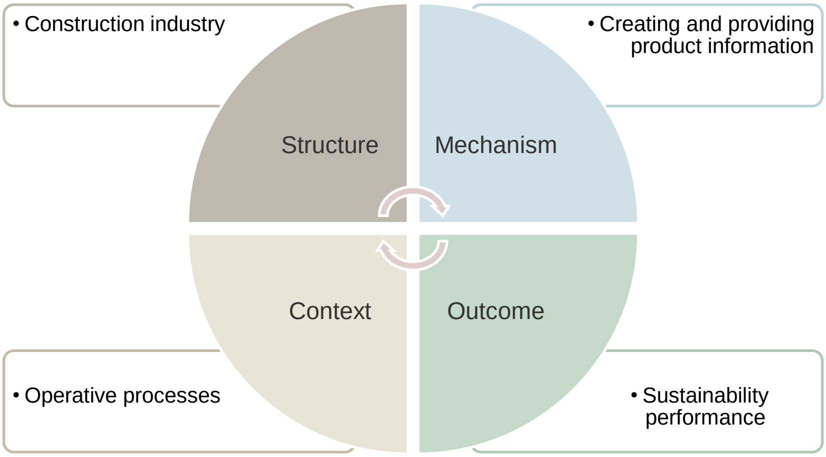


**Figure 10.** The configuration of the case study design in this research

**Table 7.** The sustainability performance indicators and operative processes in each case study

| | **Sustainability performance indicators** | **Operative processes** |
|---|---|---|
| **Case study 1 (Paper I)** | Acoustic comfort and indoor air quality | Diffusion of innovative ventilation products with enhanced sustainability performance |
| **Case study 2 (Paper II)** | Acoustic comfort | Diffusion of innovative ventilation products with enhanced sustainability performance supported by standardization of product information |
| **Case study 3 (Paper III)** | Carbon footprint, indoor environmental quality, and energy efficiency | Diffusion of innovative ventilation products with enhanced sustainability performance in BIM object library platforms |
| **Case study 4 (Paper IV)** | Fire resistance and energy efficiency | Design, manufacturing, and construction of fire-safe facades in industrialized construction |

**Table 8.** The concepts applied in each case study

| **Case study 1** | **Case study 2** | **Case study 3** | **Case study 4** |
|---|---|---|---|
| • Sustainability<br>• Information: product information and digitalization<br>• Diffusion of innovations | • Sustainability<br>• Information: product information and digitalization<br>• Diffusion of innovations<br>• Standardization | • Sustainability<br>• Information: product information quality and software usability<br>• Diffusion of innovations<br>• Digital platform ecosystems | • Systems thinking<br>• Sustainability<br>• Information: product information quality and software usability<br>• Standardization<br>• Industrialized construction<br>• Design for sustainability |

As mentioned in section 2.2.4, diffusion of innovation is a communication process through which the information about a new offering is transferred. Therefore, this phase of innovation is employed as a proper context to explore how the existing mechanisms of the creation and supply of product information affect the adoption of products with enhanced sustainability performance.

The first case study has focused on the acoustic performance of ventilation products as part of the Urban Tranquillity project (Interreg, 2018). In addition, indoor air quality is included to address the interactions between competing performance criteria by systems thinking. The findings from the first cases study show that inconsistent methods of presenting product information by manufacturers could impede the diffusion of innovative products with enhanced sustainability performance. Therefore, Case study 2 focuses on the concept of standardization concerning product information and related mechanisms.

The second case study identifies the central role of software provider companies in delivering product information for BIM applications. Since those companies use digital platform ecosystems, this concept has been added to the conceptual framework of this research. In the third case study, this concept has been applied to examine two BIM object libraries. The first three case studies apply systems thinking by including operative elements and processes and their interactions.

In Case study 4, the concept of systems thinking is the fundamental concept that embraces other concepts. The study emphasizes the building users' health and safety as a significant sustainability aspect, which is inevitably linked to the social, environmental, and economic aspects. In addition, the concepts of design for sustainability and industrialized construction are included to study the fundamental issues relating to product information in design, manufacturing, and construction. Thus, Paper IV does not discuss the diffusion of innovative products distinctively to address the problems of building product information, which still has implications for research on the diffusion of innovative products.

### 3.2.1 Data collection and analysis

In qualitative research, data collection, data analysis, and writing the results are interrelated and often concurrent processes (Creswell and Poth, 2018, p. 185). In this type of research, data is collected in natural settings sensitive to the objects under study (Creswell and Poth, 2018, p. 61).

The qualitative case study approach relies on various sources of evidence (Yin, 2018, p. 126), including observations, documents, reports, audiovisual materials, and interviews (Creswell and Poth, 2018, p. 104). The observations can be participant observation (Bell et al., 2019, p. 36) or internet-mediated observation (Saunders et al., 2019, p. 408). Traditional participant observation involves collecting primary data; however, internet-mediated observation enables researchers to apply observational techniques to primary and secondary data (Saunders et al., 2019, p. 380). In this research, an application of internet-mediated observation was observing HVAC designers using BIM objects in educational and marketing videos.

In line with the aim of this research and the objectives of the case studies (section 1.1), data have been collected from various sources listed in Table 9, and different strategies are developed for data analysis in each case study.

**Table 9.** The sources of data in this research

| | Sources of data |
|---|---|
| **Case study 1** | • Literature on sustainability, diffusion of innovations, and the acoustic performance of ventilation systems<br>• Product technical data sheets<br>• Product catalogs<br>• Product selection software<br>• Expert interviews |
| **Case study 2** | • Literature on sustainability and standardization concerning product information and diffusion of innovations<br>• Standards published by ISO, CEN, and SIS<br>• Standard organizations' websites<br>• Expert interviews |
| **Case study 3** | • Literature on sustainability, information quality, software usability, diffusion of innovations and digital platforms<br>• BIM object library websites, YouTube channels, and LinkedIn pages<br>• BIM objects of ventilation products from different BIM libraries<br>• Internet-mediated observation of using BIM objects in HVAC design<br>• Participant observation of HVAC design process using BIM objects and manufacturer's plugins<br>• Expert interviews |
| **Case study 4** | • Literature on sustainability, systems thinking, information quality, software usability, DfMA, and industrialized construction<br>• Codes, guides, and documents on facade design and fire resistance of facades published by authorities<br>• BIM objects of facade products from different BIM libraries<br>• The digital tool developed by NFPA for exterior facade fire evaluation and comparison<br>• Ansys GRANTA EduPack software<br>• Expert interviews |

Interview is commonly used as a data collection method because of its potential to provide in-depth information relating to participants' experiences (Mann, 2016a, p. 2). A professional interview has a purpose and requires a specific approach and proper techniques (Brinkmann and Steinar, 2018, p. 14). In this research, qualitative interviews were conducted to complement the data collected from other sources and ensure the interpretive validity (Huberman and Miles, 2002, p. 345) of findings.

First, questions were listed and categorized based on the products and processes. The next step was a systematic search for the experts in those products and processes who could provide the required information. The experts were selected on the LinkedIn website using two search criteria: their profession and their organization's core business.

In the case of specific products (e.g., the innovative HVAC system in Paper I), the experts who could provide accurate information (e.g., the R&D manager) were selected from the relevant organization (i.e., the HVAC manufacturing company). Then, an interview appointment was arranged through either a LinkedIn message or an email. Furthermore, the snowball-sampling technique (Gerson, 2020) was used to find the experts who could answer precise questions. For example, an R&D manager introduced a laboratory engineer who provided detailed information on recording and documenting product test results.

In total, 68 qualitative interviews with experts in various fields applicable to this research have been conducted (see Table 10). The interviews were semi-structured, regarded as professional conversations (Mann, 2016b, p. 48) searching for qualitative knowledge (Brinkmann and Steinar, 2018, p. 15). Since the required information included technical details, the interviews were in-depth. An in-depth interview requires formulating questions considering each participant's experience (Saunders et al., 2019, p. 146). Therefore, for each interviewee, a set of questions was formulated. Table 11 presents a representative selection of those questions.

Semi-structured interviews enable researchers to grasp both the information and the meanings (Brinkmann and Steinar, 2018, p. 14). The interviewer must encourage the interviewee to provide detailed descriptions (Brinkmann and Steinar, 2018, p. 62). In other words, a qualitative semi-structured interview is a co-construction of (an explanation about) reality by the interviewer and interviewee (Mann, 2016b, p. 50). Accordingly, although the questions were prepared before the interviews, additional questions were asked depending on the interviewees' answers. The intention was to understand the meanings of the interviewee's descriptions without imposing the researcher's own expectations and assumptions.

The interviews were recorded, and the recordings were transcribed and analyzed after each interview. The findings were used to enhance the plan for the next step of the data collection process. During the final analysis, the raw transcripts were used in order to avoid excluding essential and helpful information.

**Table 10.** The list of the interviews conducted in this research

| | Number of interviews | Experts' professions | Number and core business of organizations |
|---|---|---|---|
| **Case study 1** | 17 | Marketing manager, Product and marketing manager, R&D manager, Vice president – Sales, System development director, Sales manager, Key account manager, Project engineer – Control and system solutions, Sales engineer, Marketing coordinator – Commercial ventilation, Laboratory engineer | 3 HVAC manufacturing companies |
| | | R&D manager | 1 wireless technology company |
| | | Business developer, Business manager – Market development, Project manager, HVAC design engineer, Acoustic consultants | 4 AEC companies |
| **Case study 2** | 25 | CEO, Chief operating officer, System specialist, Product manager, QMS & EMS coordinator, Laboratory engineer, R&D manager, IT solutions manager, Project support coordinator | 6 HVAC manufacturing companies |
| | | Chair of the technical advisory board | 1 sector association (BIM) |
| | | Technical and environmental manager | 1 sector association (ventilation) |
| | | Area manager Scandinavia – BIM services for manufacturers | 1 HVAC design software provider |
| | | Development manager, Construction engineer, Assignment manager – HVAC, HVAC design engineers | 5 AEC companies |
| | | HVAC consultant, Acoustics consultants, Director of engineering, Acoustician | 3 consultancy companies |
| | | Chairperson – Technical committee, Project manager, Project assistant | 1 standards organization |
| **Case study 3** | 8 | Area Manager, Global technical director | 1 BIM object library provider |
| | | Manager – IT solutions, Process leader – Marketing & Communication, Product manager | 3 HVAC manufacturing companies |
| | | HVAC design engineer, Energy engineer – HVAC | 2 AEC companies |
| **Case study 4** | 18 | Structural and facade engineer, facade engineers | 3 facade engineering companies |
| | | Director – Facade engineering, Director, Fire and risk engineer, Digitalization manager, Director – IoT | 3 AEC companies |
| | | Founder | 1 facade automation engineering company |
| | | Facade engineer | 1 Facade design and manufacturing company |
| | | Global product manager, Research engineer | 2 Manufacturing companies |
| | | Automation lead | 1 design, engineering, and management company |
| | | Researcher (Digital Twin) | 1 university |
| | | Product development manager | 1 simulation software provider |

**Table 11.** The examples of the interview questions in this research

| Expert's profession | Sample questions |
|---|---|
| Laboratory engineer at HVAC manufacturing company | What standard test methods do you use for the acoustic performance of air diffusers?<br>How do you document and report the results?<br>Why are the acoustic data for circular and rectangular dampers presented in different ways?<br>What is the reason for using A-weighted equivalent sound power levels to present the data?<br>When the equivalent A-weighted sound pressure level $L_{pA}$ is read from the plots, it should be converted to sound power levels in octave bands $L_w$[dB] through applying a constant $K_{oc}$, i.e., $LW=L_{pA}+K_{Ok}$. Is this constant used for both sound pressure and sound power level conversion?<br>Why is it not specified in the datasheet? |
| IT solutions manager at HVAC manufacturing company | What BIM library platforms do you participate in?<br>How do you create a BIM object for platform B?<br>Is there any standard/requirement you should follow regarding the information included in the BIM objects?<br>Do you pay for creating BIM objects and maintaining them in platform A's library?<br>What are the reasons for having limited BIM objects in BIM libraries?<br>How do you decide which products should have BIM objects?<br>How do you update your BIM objects on platform A? |
| Technical director of BIM object library | What are your strategies to attract manufacturers to your platform?<br>What are your strategies to attract designers to your platform?<br>How do you get product information from manufacturers?<br>Should they send their product data in any specific formats?<br>Do they have to follow any standards for the product information?<br>Are there any requirements regarding the contents of the product data (e.g., the energy performance or acoustic performance of a fan)?<br>How do you control the quality of BIM objects? Is any certification required? |
| Facade engineer | What are the stages of a typical process of facade system design at your company?<br>How do you think this process can be improved?<br>What qualifications are required to work as a facade engineer at your company? Is any specific certification required?<br>How do you consider the risk of fire during material selection?<br>How do you review the information provided by manufacturers about the fire resistance of their facade materials?<br>Do you think the information is usually understandable for facade designers?<br>How do you make sure that the information is correct?<br>How is the fire resistance of a designed facade tested? Whose responsibility is that?<br>What tests and standards are used? |

Qualitative researchers use both inductive and deductive reasoning to analyze the data and establish patterns or themes (Creswell and Poth, 2018, p. 43), emphasizing words rather than quantifications (Bell et al., 2019, p. 35). This strategy has been employed to analyze the collected data in this research. The method used for data analysis is “explaining outcome process tracing”, which is a well-established method to study causal mechanisms in qualitative in-depth case studies (Beach and Pedersen, 2016, p. 309). This case-centric method involves moving between inductive and deductive paths until the best explanation for causal mechanisms that account for the outcomes is proposed (Beach and Pedersen, 2016, p. 277).

For each case study, however, a data analysis strategy in accordance with the objective of the study has been developed. Figure 11 shows the stages of data analysis in Case study 1, which is based on the data analysis spiral suggested by Creswell and Poth (2018, p. 186) and the explaining outcome process tracing method (Beach and Pedersen, 2016). As mentioned previously, Case study 1 studies the flow of information on the acoustic performance of an innovative ventilation system. The words and notations representing the sustainability attributes of the products (system components) are coded and categorized into three themes: awareness knowledge, how-to knowledge, and principles knowledge about the products in the digital documents and product selection software.

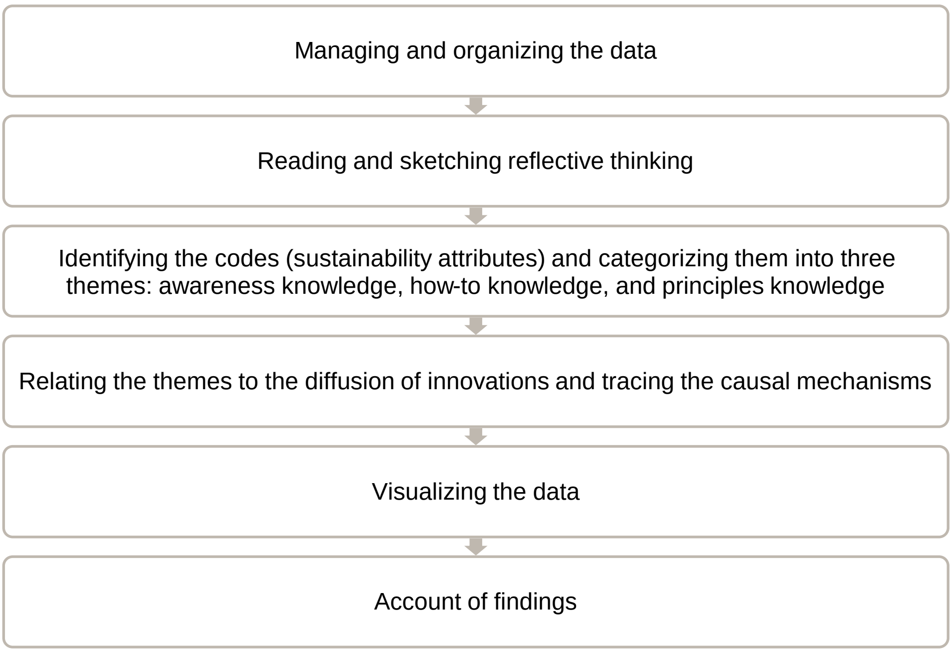


**Figure 11.** The stages of data analysis in Case study 1 (After Creswell and Poth, 2018)

The second case study explores the standards on the acoustic performance of ventilation products. Figure 12 presents the data analysis in Case study 2, including two interrelated processes: an analysis of the standards on the acoustic performance of the ventilation products accompanied by an analysis of the flow of product, the flow of product information, and the stakeholders involved. As illustrated in Figure 12, identifying the suppliers facilitated the collection of the relevant standards. Account of findings from the two processes was concluded concurrently.

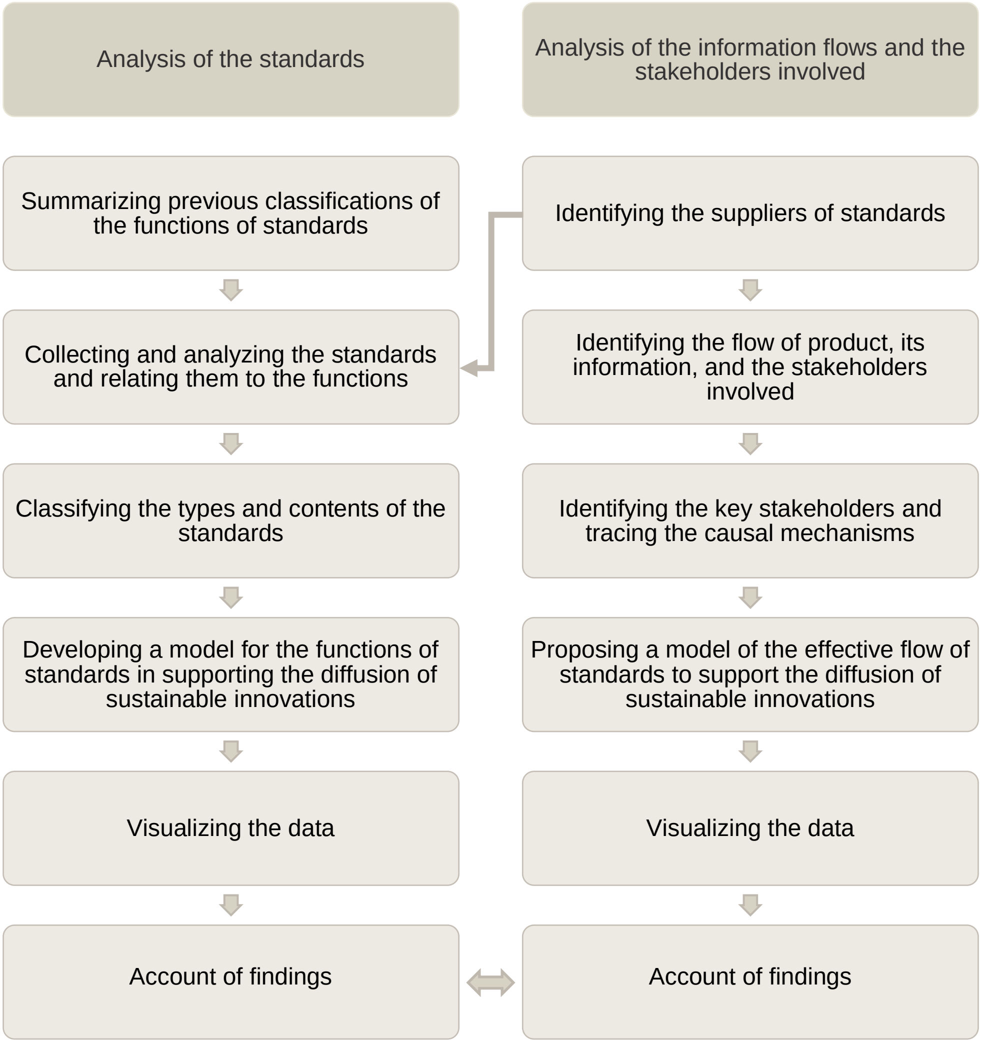


**Figure 12.** The stages of data analysis in Case study 2

The third case study adopted a multiple-case study approach to study two cases: Case 1 (Platform A) and Case 2 (Platform B). As Figure 13 presents, the embedded units of analysis (Yin, 2018, p. 48) in each case are platform participants, BIM library interface, and the BIM objects offered by the library. The stages of data analysis are illustrated in Figure 14. This strategy is developed by integrating the data analysis spiral (Creswell and Poth, 2018, p. 186), the template for coding a multiple-case (Creswell and Poth, 2018, p. 218), and the explaining outcome process tracing method developed by Beach and Pedersen (2016).

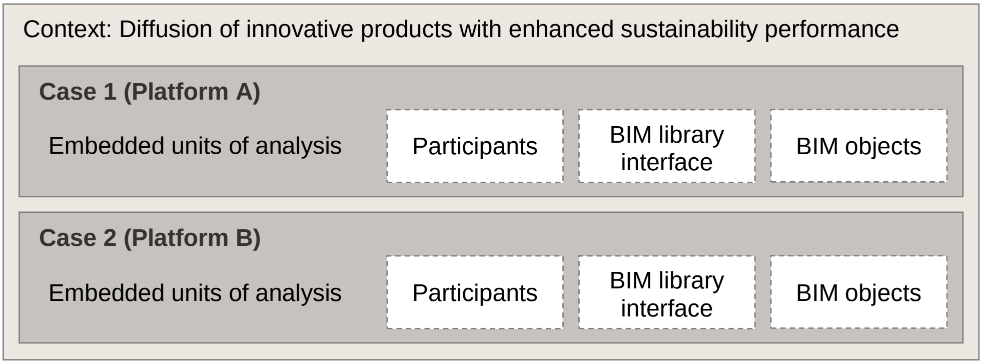


**Figure 13.** The contexts and units of analysis in Case study 3 (Adapted from Bahrami et al., 2019)

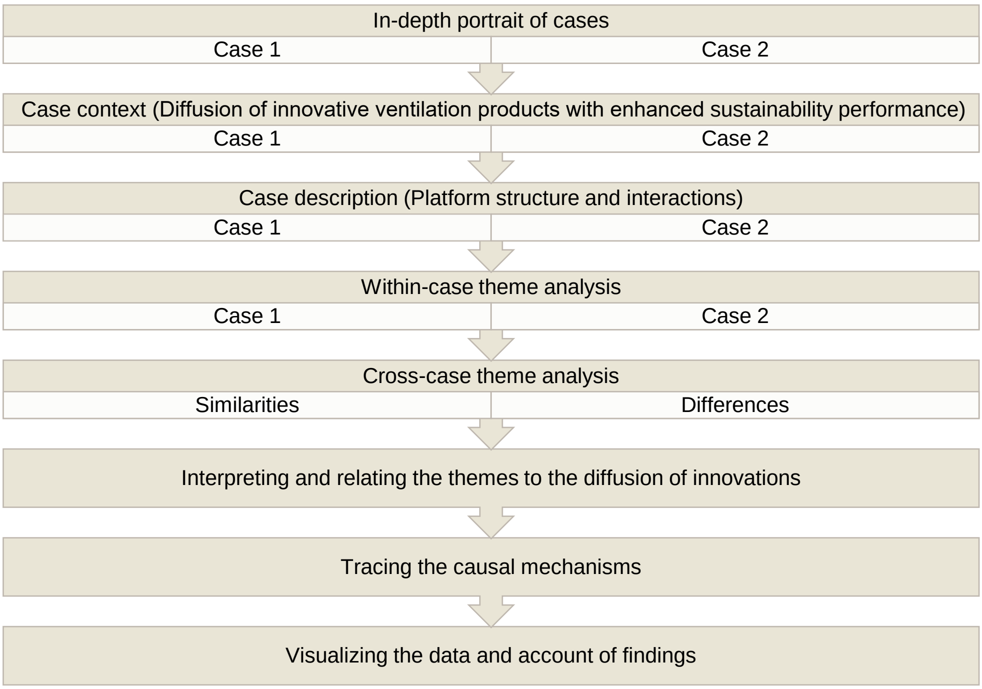


**Figure 14.** The stages of data analysis in Case study 3 (After Creswell and Poth, 2018)

The fourth case study presented in paper IV is a single-case study on the design defects that cause the rapid spread of fire in facades. As illustrated in Figure 15, this case has four embedded units of analysis. The inspiration for this design is gained from Toyota's eighth management principle that emphasizes *technology* to support *people* and *processes* (Liker, 2020, p. 7) and integrating these three elements in a product development system (Morgan and Liker, 2006). It has been modified by adding *information* as an essential element and limiting the elements to the aspects that specifically relate to the objective of the case study. Those aspects have been determined as the units of analysis, i.e., information on the fire resistance of facade products, design procurement and implementation processes, the usability of digital tools and databases, and designers' knowledge and expertise.

These units of analysis have been used in two sequential stages of data analysis in Case study 4. The reliability of data is determined by the extent to which the data collection and analysis techniques will yield consistent findings (Saunders et al., 2019, p. 518). To ensure the reliability of findings from examining the usability of software and digital tools, test scenarios were designed and followed in the trials repeatedly. For example, the author used the design scenario presented in Paper IV in 50 trials for testing the NFPA's digital tool, and the co-author repeated the trials to confirm the consistency of the findings. Those trials are visualized in Figure 4 in Paper IV.

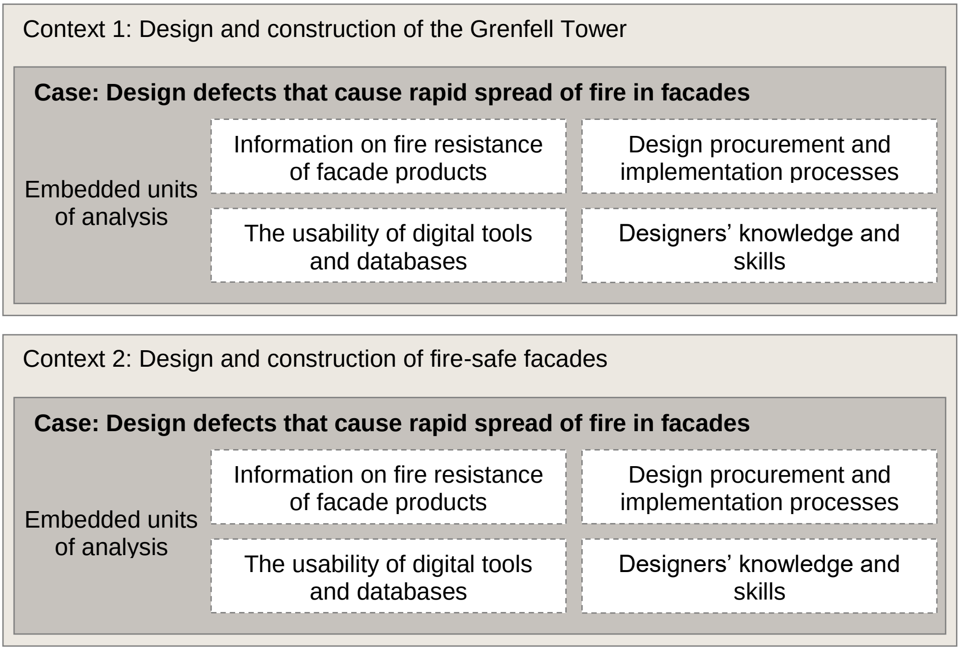


**Figure 15.** The contexts and units of analysis in Case study 4

Figure 16 illustrates two sequential stages of data analysis in Case study 4. As can be seen, the findings from the first stage have been used to conduct the second stage. In other words, the design and construction defects that caused the rapid spread of fire in the Grenfell Tower facade have been studied in a new context (i.e., design and construction of fire-safe facades) to see how those problems can be avoided early in the design stage of a facade life cycle.

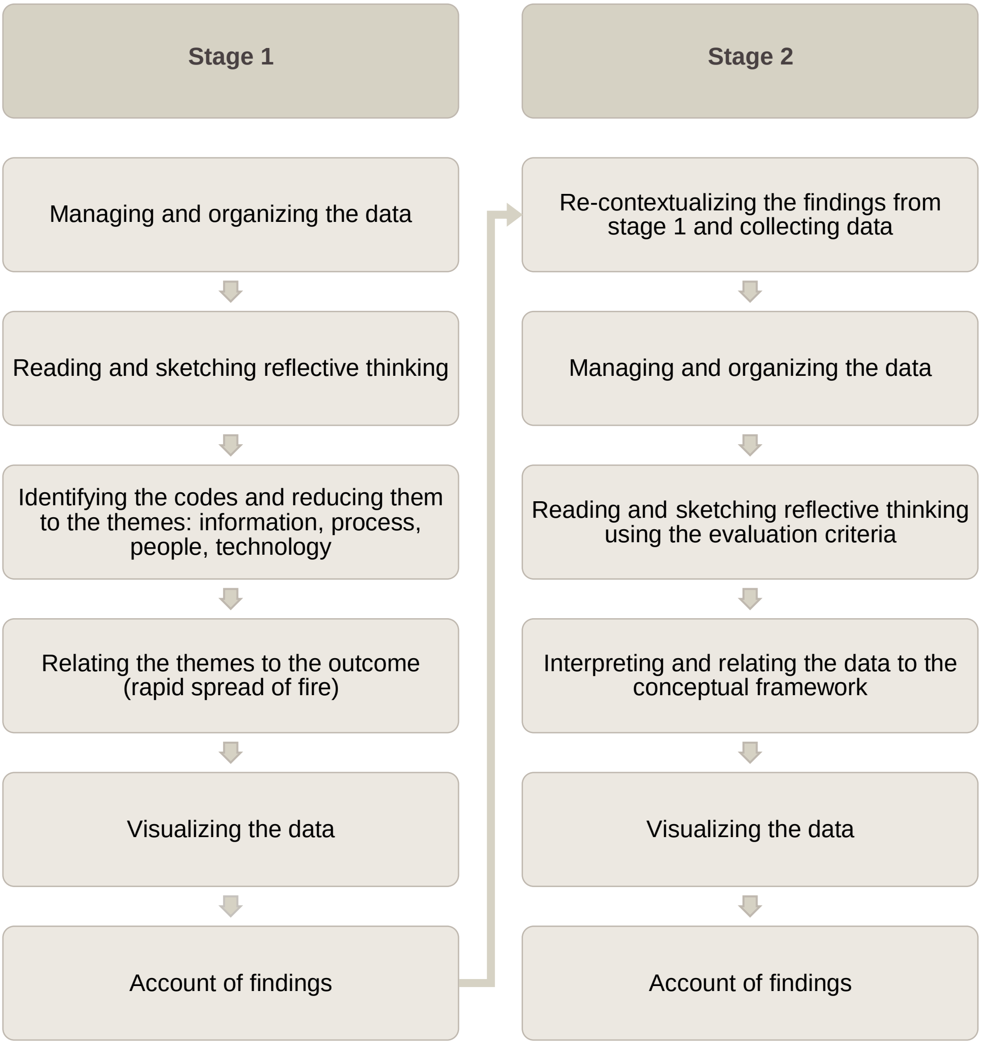


**Figure 16.** The stages of data analysis in Case study 4

As shown in Figure 17, the findings from the case studies have been analyzed iteratively to enrich the conceptual framework and confirm the findings. Finally, a cross-case analysis of the findings from the four case studies has been performed. This form of analysis involves examining themes across the cases (Creswell and Poth, 2018, p. 322) and enables the synthesis of the findings from the case studies included in a qualitative study (O'Leary, 2016). The concepts presented in the conceptual framework (section 2.1) are the themes examined in the cross-case analysis and synthesis process. The process has enabled proposing logical explanations for the identified events and mechanisms and suggestions for improvements. These processes follow the model in Figure 9 (section 3.1), presenting the stages of this research in the framework of critical realism. In addition, two models have been developed based on this analysis, which will be presented in Chapter 5.

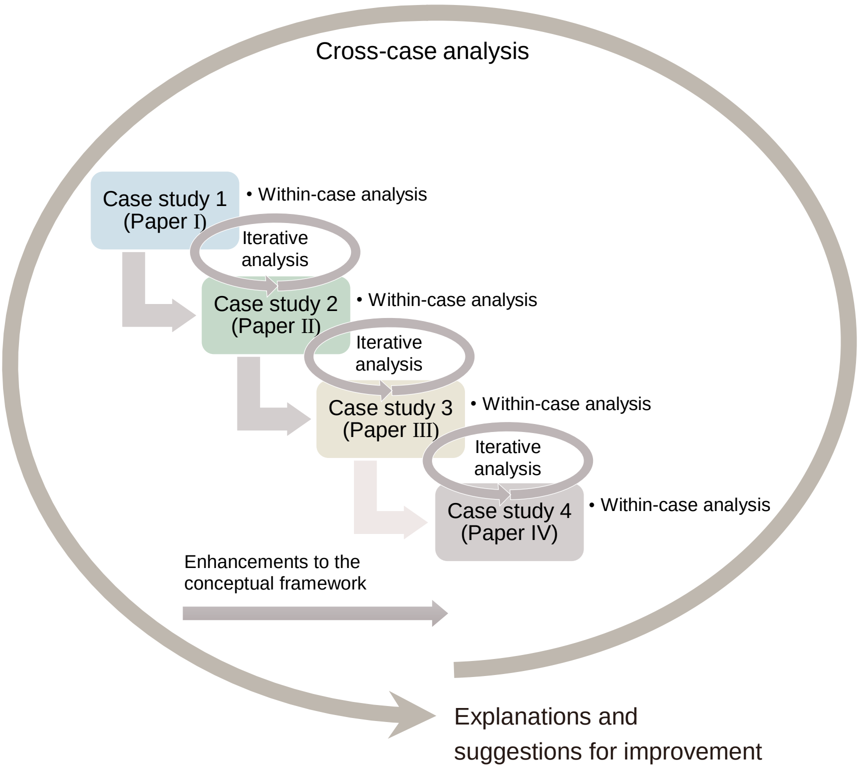


**Figure 17.** The data analysis process in the framework of critical realism

# 4 Discussion of Findings

## 4.1 Findings from Case Study 1

The first case study, presented in Paper I, aimed to investigate how a manufacturer communicates the information on the acoustic performance of its innovative demand-controlled ventilation (DCV) system with the users of the information during the diffusion phase of the innovation.

The findings show that the capability of the innovative DCV system for improving acoustic comfort is not mentioned in the product information presented by the manufacturer. In addition, problems of inadequacy and inaccuracy of product information are identified in the product selection software and digital documents. Because of the incomplete information provided by the manufacturer, designers and purchasing agents in AEC companies might undervalue the system. The findings also indicate that the indoor noise generated by the DCV system components is mainly because of incorrect applications. The root cause is the selection of incompatible products by either building HVAC designers or purchasing agents. Incorrect installation by HVAC technicians is another underlying cause of the noise generated by the DCV components. The study suggests that such problems can be prevented by providing product information that is adequate and appropriate for each group of users.

In the Swedish building codes, the requirements for the acoustic performance of ventilation products reference the measurement test standards. However, the study shows that the standards used for testing the DCV system components are seldom mentioned in the product information (e.g., product data sheets and product selection software). As a result, the availability of the information on the measurement methods and the user’s ability to analyze the acoustics data are limited.

Case study 1 also reveals that manufacturers employ inconsistent methods for presenting the acoustic performance of their products. For example, they use different terms, units, notations, and illustrations (tables and diagrams) for presenting the same acoustic property (e.g., sound pressure level). As a result, building HVAC designers and purchasing agents could not directly compare the acoustic performances of similar products by various manufacturers that could impede the diffusion of innovative products with enhanced acoustic performance.

From a critical realist perspective, the first case study provides an abductive redescription of the mechanisms that affect the information on the sustainability performance of an innovative product. The deficient mechanism of providing information has created a significant gap between the actual and empirical domains. In other words, the actual performance of the DCV system cannot be understood because of incomplete information available as empirical evidence.

## 4.2 Findings from Case Study 2

The findings from the first case study drew attention to the standardization of product information and understanding its role in supporting the diffusion of innovations. Therefore, the second case study, presented in Paper II, has explored the standards on the acoustic performance of ventilation products, their functions in supporting the diffusion of innovations, the flows of information, and the stakeholders involved.

The analysis on the supply side of the standards has identified the stakeholders involved in adapting, developing, and establishing the standards on the acoustic performance of ventilation products (see Fig. 2 in Paper II). The Swedish Institute for Standards (SIS) is the key stakeholder on the supply side of the standards. In addition to developing and publishing national standards, SIS collaborates with the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) to supply international and European standards in Sweden. This makes the SIS website the primary source of information about the existing standards.

The analysis of the standards provided by SIS and the classifications of standards suggested by previous studies shows the necessity of a novel approach to classify the standards. Accordingly, the existing standards on the acoustic performance of ventilation products are classified into two types of technical and management system standards (see Table 3 in Paper II). This classification facilitates the study of the functions of standards concerning the diffusion of innovations.

Since the categorization of functions of standards in supporting innovations suggested by previous studies is inapplicable to Case study 2, a new model for presenting the functions of standards on product information is developed (see Fig. 3 in Paper II). The previous classifications considered *information* and *variety reduction* as two functions of standards in supporting innovations. Furthermore, the study suggests that *information* is not a function but the content of all standards. Thus, the study recommends that *information* be replaced by two functions: *identification* and *comparability*. This recommendation is justified by the fact that standards facilitate identification, traceability, and comparison of products by supplying codified information.

The analysis of the standards on the acoustic performance of ventilation products shows that although standardizing the product characteristics limits the variety of products, it ultimately facilitates manufacturing standard components, which can be used in various ventilation systems. Thus, Case study 2 proposes replacing *variety reduction* with *compatibility and interface*. This function is suggested for harmonizing data formats and providing an interface for exchanging harmonized product information.

Furthermore, the study identifies *performance* as the main function integrated with other functions of standards and defines it as “the ability of a ventilation product to fulfill the user requirements during its operation in a building that includes quality, health and safety, environmental, and economic performance”. Finally, *improvability* is introduced as an essential function of standards. This function is fulfilled through regular reviews of the standards by standard organizations and continual improvement processes required by management system standards.

Previous studies tabulated their classifications of the functions of standards, even though some functions overlap each other. As a result, the relations between the functions are not clear in those tables. Case study 2 proposes a new model for illustrating the functions of standards (see Fig. 3 in Paper II). The model shows that the standards on product information have five functions: *identification*, *comparability*, *compatibility and interface*, *performance*, and *improvability*. Moreover, the model highlights the central role of standardized product information in supporting the diffusion of innovations.

Tracing the flow of product information and the stakeholders involved identifies the manufacturers, engineering services firms, and the software companies offering BIM tools as the key stakeholders (Fig. 4 in Paper II). It shows that the engineering services firms’ demands for both products and modeling software have created a market-mediated interdependence between the HVAC manufacturers and the software companies. That gives a pivotal role to the software companies in generating demand for standardized product information (see Fig. 5 in Paper II).

In Case study 2, systems thinking and a process tracing method have been applied to identify the supply system of standards (Fig. 2 in Paper II), the functions of the standards (Fig. 3 in Paper II), and the flow of product information and the stakeholders involved (Fig. 4 in Paper II). Identifying the system elements and processes enabled developing a model for supplying and applying the standards to support sustainable innovations (Fig. 5 in Paper II). In the framework of critical realism, the study identifies efficacious mechanisms for providing information on the sustainability performance of products. These mechanisms could reduce the gap between the domains of the actual and empirical, which was identified in the first case study. These findings have formed the basis for the third case study.

## 4.3 Findings from Case Study 3

As mentioned previously, the findings from the second case study point toward the central role of software companies in providing product information for BIM applications. Hence, the third case study focuses on two BIM object library platforms supplying BIM objects of ventilation products (see Paper III). The objective is to understand how these platforms can be improved to support the diffusion of innovative ventilation products with enhanced sustainability performance. The matrix shown in Fig. 3 in Paper III and the questions listed in Table 2 in Paper III have been developed to collect and analyze the data from the two BIM object library platforms, named platform A and platform B in the paper.

Typically, software providers (platform owners) facilitate interaction between building product manufacturers and AEC companies in these platform ecosystems. However, this case study identifies problems regarding the core interaction (the creation and exchange of information on the platforms) and its three key elements: participation, BIM object library interface (website), and BIM objects. These problems can impede the diffusion of innovative ventilation products with enhanced sustainability attributes.

Fig. 4 and Fig. 5 in Paper III illustrate the interactions on platforms A and B. The findings show limited participation on both platforms. The reasons mentioned by the interviewees are the existing methods of creating BIM objects and the high cost of creating and maintaining manufacturer BIM objects on the libraries. The HVAC brands available on platform B are 3.4 times fewer than the brands on platform A. This can be explained by the differences in the strategies adopted by the platform owners.

Platform A targets the mechanical, electrical, and plumbing (MEP) sector. It generates profit by creating BIM objects and plugins as well as selling MEP design and calculation software. Platform A is a closed system, which is easier to monetize and control. Moreover, it enables the platform owner to allocate professional resources and satisfy user requirements for HVAC applications. This, together with the dependency of HVAC designers on the design software offered by the company, can explain the higher participation on this platform. In contrast, Platform B is open to various BIM users and generates profit by selling software for creating BIM objects and BIM-based solutions. Adopting this strategy might enable platform B to absorb innovative solutions developed by participants for creating BIM objects.

Case study 3 shows that improper website architectures and inadequate product information have limited the usability of the BIM object library interfaces in supporting the diffusion of innovative products. The study identifies problems associated with the availability of BIM objects, searchability of the content, and comparability of different brands based on the sustainability attributes of the products. Inadequate participation on the platforms has reduced the access to information about the existence of innovative products (awareness knowledge). As a result, the number of BIM objects is very limited compared to the number of products in the market. Neither of the platforms enables its users to search for BIM objects based on the sustainability attributes of the products. Similarly, comparing products based on their sustainability attributes is impossible on both platforms.

The BIM objects on platform A are compatible with Revit and the design software offered by the platform owner. Platform B's objects are also compatible with Revit and AutoCAD. However, neither of the platforms' objects suffices to perform accurate calculations. Thus, HVAC designers need plugins to access manufacturers' selection and calculation tools. The errors in the product information remain in its BIM objects because neither of the platform owners controls the accuracy of product information provided by manufacturers. Both platforms provide inadequate information on the sustainability attributes of products. Therefore, users must obtain the information by either searching on the manufacturers' websites or contacting manufacturers directly outside the platforms.

Problems such as confusing terms, notations, and units used in manufacturers' data sheets have lowered the comprehensibility of the BIM object contents on both platforms. In addition, neither of the platforms enables its users to see whether the product information is up to date. Since manufacturers use heterogeneous methods for presenting the sustainability performance of their products, comparing different brands and choosing products with better sustainability attributes is impossible on both platforms.

Applying systems thinking in Case study 3 has facilitated the accurate identification of the participants and their interactions on the platforms, which are shown in Fig. 4 and Fig. 5 in Paper III. This, in turn, has enabled identifying efficacious concepts (information quality and software usability) and mechanisms (providing product information on BIM object libraries) to support the diffusion of sustainable innovation as the objective of this critical realist study.

## 4.4 Findings from Case Study 4

The fourth case study aimed to investigate the quality and flow of facade product information concerning fire safety, the design defects underlying fire spread in facades, and the capabilities for avoiding those defects (see Paper IV). As mentioned in Chapter 1 (Introduction), Case study 4 is influenced by the Grenfell Tower tragedy and the problem of facade fires worldwide. From a critical realist viewpoint, the study identifies fire safety performance as an efficacious concept interconnected with social, environmental, and economic impacts in the built environment. The iterative correction of earlier findings in the light of this identification (stage 5 in Figure 9, section 3.1) broadened the context to include both innovative and standard products. Accordingly, the context in Case study 4 has been changed from the diffusion of innovative ventilation products to the design, manufacturing, and construction of facade products. Concerning sustainability performance, the study focuses on the fire safety performance and the energy efficiency of facade products to highlight the need for systems thinking in adopting sustainable design strategies.

The first stage of the study categorizes the fundamental problems that caused the fatal consequences of the Grenfell Tower fire. As described in Table II in Paper IV, these failures are linked to product information problems (e.g., disinformation regarding the fire test results supplied by manufacturers) and design and installation defects (e.g., selection of noncompliant materials, defective installations, and noncompliant installations). This categorization forms the basis for Figure 3 in Paper IV, which identifies potential problems and relates them to the design and construction stages of a facade life cycle. Also, the figure shows how misleading product information can flow through the life cycle of a facade system because of limited professional expertise.

Another important finding of the first stage is the risk of incomplete conclusions in a series of research publications relating to the Grenfell Tower fire incident. The incautious interpretations in those publications run the risk of tragic consequences of facade fires because such publications might be consulted in the design and regulatory decision-making processes.

The second stage of the study explores the capabilities for avoiding the problems identified in the first stage. This stage analyzes the expert interviews, regulatory documents, and three digital interfaces (see Table I in Paper IV). According to the interviewed facade professionals, the fragmentation of design processes can cause communication and coordination problems and, subsequently, increase the risk of design errors. Senior facade designers are critical of the adequacy, accuracy, and understandability of the information on fire resistance of facade products. However, the junior facade designers have mentioned that manufacturers undoubtedly provide accurate and reliable product information because they cannot compete in the market if they provide inaccurate information. Based on that argument, they believe it is unnecessary to review the details of fire test results in product documents.

In addition, facade engineers expressed various perspectives regarding professional responsibilities. Some pointed to a critical review of the drawings and design proposals and on-site inspections as necessary measures to avoid the risks of fire and liability problems. In a few responses, however, there is a tendency to transfer the responsibility to others and rely entirely on the information provided by other specialists. An interesting finding of Case study 4 is the variety in the facade designers' background knowledge, which shows the essential need for work experience and professional certifications, which is also necessary for facade installers in order to avoid defective installations. In addition, accurate installations require reliable installation instructions.

The interviewees experienced in industrialized construction and DfMA believe that applying standardized solutions in industrialized construction can reduce design errors because the modules are designed and optimized more efficiently compared to traditional construction methods. They also indicated that the high-level integration required for DfMA facilitates design coordination and collaboration. Moreover, the consistency created by DfMA can create consistency in supply chains because the product requirements can be articulated, requested, and controlled. However, Paper IV suggests that the success of DfMA in supporting sustainable design and construction requires integrating the sustainability objectives, particularly the fire safety of facades, into DfMA.

The investigation of digital interfaces reveals information and interface quality problems regarding availability, searchability, comparability, traceability, understandability, currency, accuracy, adequacy, and consistency. The results of examining the NFPA's digital tool show it could enhance the knowledge of code requirements among facade designers. However, its usability has been limited by outdated information and functional defects in the navigation structure.

The results from the evaluation of the BIM libraries indicate that deficient product information provided by manufacturers has affected the interface quality and, consequently, limited the usability of the BIM object libraries in providing information on fire resistance of facades. The first three case studies revealed the same problem in the BIM objects of ventilation products. The analysis of the Ansys GRANTA EduPack shows that deficient product information provided by manufacturers has also impeded the usability of software for supporting the fire safety of facades in design and manufacturing processes.

Regarding the application of digital twins in facade design, the findings imply that various companies and researchers have referred to models with different levels of accuracy and optimizations as digital twins. Further advances in the existing technologies are needed to create digital twins of facades, which can evolve and interact with the physical prototypes and products throughout the entire life cycle. The application of digital twins needs continuing research considering rapid developments in digital technologies such as Microsoft Azure Digital Twin and Autodesk Tandem.

## 4.5 Summary of Discussion

This research has sought to answer how the quality of building product information and the usability of the interfaces providing such information can be improved to support sustainability in the built environment. The findings from Case studies 1, 2, and 3 reveal fundamental problems regarding the understandability, currency, accuracy, and adequacy of information on the sustainability performance of products and the consistency of the methods for presenting this information. Regarding the interfaces, this research identifies fundamental defects in the availability, searchability, comparability, and traceability of product information in the BIM object libraries and material databases. These defects must be addressed to improve information quality and software usability in the interfaces to support sustainability in the built environment. However, systems thinking on this issue suggests that improvements in interface quality cannot occur without improving the provision of product information by manufacturers. This is of particular importance in industrialized construction, influenced by manufacturing principles.

The findings from Case study 2 suggest that standardization of product information can improve the quality of the information provided by manufacturers. From a critical realist viewpoint, it can generate an efficacious mechanism for providing product information to support sustainability. However, systems thinking is required to understand the functions of standards and develop this mechanism properly. Thus, the study proposes a model for the functions of standards (Fig. 3 in Paper II) and their relations. These functions ensure the identification, comparability, compatibility, performance, and improvability of sustainable products. In addition, the study suggests that proper enforcement of the standards requires operative legislation.

Systems thinking is the fundamental concept in the fourth case study. The concepts of design for sustainability and industrialized construction are included to study the problems of product information in design, manufacturing, and construction. The findings show how linear approaches to sustainable design can lead to tragic consequences in the built environment. This emphasizes the building users' health and safety as a significant sustainability aspect, manifestly connected with the social, environmental, and economic aspects. In addition, the study identifies fragmented design processes and limited professional expertise as the system processes and elements that must be addressed to improve the flow of information in design and construction processes. Most importantly, the study identifies misinformation and disinformation in product information and research publications. This finding implies that the successful application of critical realism needs careful attention to the reliability of the empirical domain.

# 5 Conclusions and Recommendations

This research has aimed to enrich the understanding of building product information to support sustainability in the built environment. Through systems thinking, the research has considered the built environment as a system whose primary purpose is sustainability. Product information, digital interfaces, and information users are the system elements that have been investigated. The interactions among these elements have been explored by process tracing throughout the flow of information in the design, manufacturing, procurement, and construction processes. Critical realism has been applied to understand how these processes can be improved to support the system (the built environment) towards its purpose (sustainability).

The findings show that deficient product information and digital interfaces can adversely affect sustainability in the built environment through two mechanisms. The first identified mechanism is impeding the diffusion of innovative products with enhanced sustainability performance. In other words, the examined digital interfaces cannot present the relative advantage of sustainable products. The second identified mechanism is causing design defects that can contribute to harmful incidents in the built environment, for example, facade fires. This mechanism involves deficient product information and its flow through design and construction processes. The fragmentation and limited professional expertise in the design process contribute to this flow of deficient information and increase the risk of harmful consequences.

Effective improvements towards sustainability in the built environment require systems thinking. Therefore, *sustainability* must be determined as the purpose of the system, each element of the system, and the interactions between the elements. That includes both the P-purpose (i.e., the purpose for which the information is produced) and the C-purpose (i.e., the purpose for which the information is consumed). This approach enables the creation and flow of information that facilitates the co-evolution of design and problem spaces toward sustainable design and construction.

## 5.1 Practical Implications

The findings of this research reveal major problems concerning the quality of product information and the usability of digital interfaces in the construction industry. In particular, the identified issues relating to disinformation and misinformation on the fire safety performance of products highlight the essential role of manufacturers in determining the quality of product information. The findings from the first three cases studies indicate that faster market penetration might act as an incentive for manufacturers of sustainable products to improve the quality of information on the performance of their products. However, the fourth case study reveals fundamental issues relating to the understanding of sustainability performance and integrity of manufacturers. These findings show an urgent need for effective regulations on the provision of information regarding the sustainability performance of products. The regulations must also target digital interface providers because of a rapid transition towards digitalization in construction.

Due to the variety of products and test methods, the establishment of such regulations needs functional standardization of product information. As suggested in Paper II, to support sustainable products, standards on product information require five functions that need careful attention when developing such standards. They must enable users to identify the sustainability attributes of products, make direct comparisons between different brands, and ensure the compatibility and desired performance of products. In addition, they must facilitate the improvements in product performance and the quality of its information.

The frameworks proposed in this research enable manufacturers and digital interface providers to determine sustainability as the main purpose of the information flow and make improvements towards this purpose. First, manufacturers must improve the quality of information on the sustainability performance of their products, which is a prerequisite for improvements in the usability of digital interfaces. To improve the usability of interfaces, digital interface providers need product information that is understandable, up-to-date, accurate, and adequate for sustainable design and presented by methods that are consistent across all manufacturers of the same product. Subsequently, they can improve the structure of their interfaces by enabling the availability, searchability, comparability, and traceability of the product information. Delivering improved information on the sustainability performance of products by interface providers can create digital platform ecosystems in which the value unit is sustainable. Moreover, improving the creation of information on the sustainability performance of products is required for the success of manufacturing tools such as PLM and BOM in support of sustainability in the built environment.

The findings highlight the designer’s expertise as a determining factor in detecting problems in product information and avoiding harmful design defects. A proper understanding of sustainability performance criteria, such as fire resistance, among designers reduces the risk of overreliance on others. Developing interdisciplinary knowledge can also improve communications between product designers and building designers in industrialized construction systems and facilitate the application of DfMA and sustainable approaches to design. Establishing effective professional certification programs is thus recommended.

This research pointed to the credibility of research publications as a major problem that needs careful attention. More collaborative studies are needed to achieve unbiased results that can be delivered by digital interfaces and consulted in legislation, standardization, and design processes. This research recommends establishing interdisciplinary research platforms involving researchers from different areas of related studies in collaboration with various competitors in the building product market.

## 5.2 Theoretical Implications

Overall, this research contributes to applied critical realist research on sustainability in the built environment. Figure 18 presents how this research exemplifies the application of critical realism philosophy in technological studies to approach sustainability problems systematically. It can be seen from Figure 18 that the available data and information about a product are in the domain of the empirical, which is just a part of the actualized life cycle of a product (i.e., the domain of the actual). That means the available information does not cover the entire sustainability performance of a product. Moreover, the findings of this research highlight the unreliability of the empirical domain as a considerable possibility.

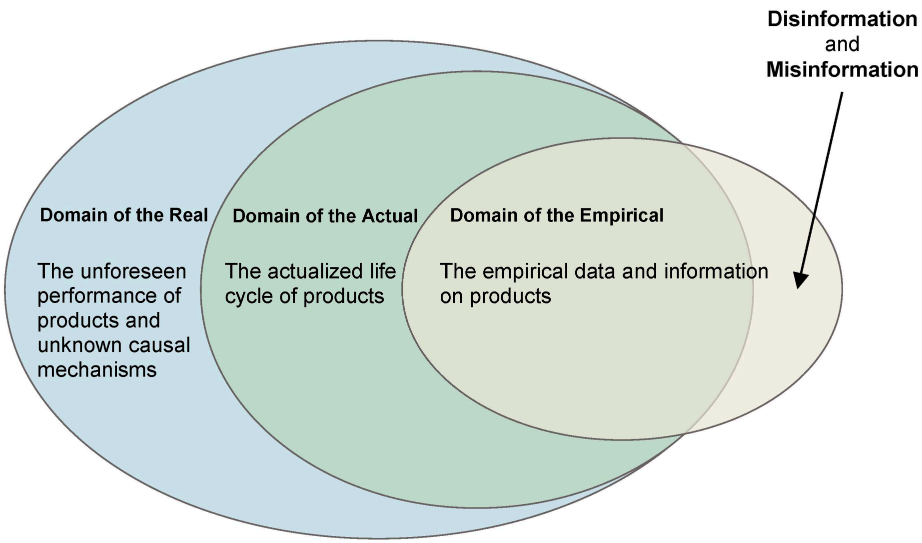


**Figure 18.** The relation between building product information and three domains of reality

Understanding the domain of the real is a significant challenge during design decision-making because of the unforeseen performance of a product and the unknown mechanisms. In other words, since every building is a new system, there are some aspects of the sustainability performance of a product that might not manifest until the product is operational in the domain of the real. The concept of predictive digital twins seems a promising solution to this problem. However, the biggest challenge is the disparity between the domain of the empirical and the domain of the actual, which is twofold: the gap created by unavailable information regarding the actualized life cycle of products and the dissemination of disinformation and misinformation.

As the first step in this research, Case study 1 provides an abductive redescription of the mechanisms influencing the information on the sustainability performance of an innovative product. This forms a basis for Case study 2, which proposes a new classification (Table 3 in Paper II) and a model (Fig. 3 in Paper II) for the functions of standards on the acoustic performance of ventilation products. Both the classification and the model can facilitate the in-depth analysis of standards in studies on the sustainability performance of products.

Case study 3 appears to be the first study to develop and apply a framework (Fig. 3 in Paper III) for evaluating the information quality and software usability in BIM object library platforms. The research methodology in the study forms a solid basis for applying critical realism in technological case studies. It shows how to apply abductive redescription, re-contextualize the components of a conceptual framework, and implement retroduction of possible explanatory mechanisms and structures. The framework (Fig. 3 in Paper III), together with the questions provided in Table 2 (in Paper III), is helpful for qualitative studies on software usability and information quality in the construction industry. As a practical example of applied critical realist research, Case study 4 presents how the proposed framework in Paper III can be customized to evaluate different digital tools.

Based on a cross-case analysis and synthesis of the data collected in this research, a conceptual model is proposed for creating and exchanging product information in sustainable design and construction (Figure 19). The model conceptualizes systems thinking in co-evolutionary design and construction. It can be applied in research on digitalization and industrialized construction while considering the limitations of this research.

As shown in Figure 19, the physical and virtual life cycles of a product are explicitly geared towards the sustainability performance of the product. The virtual life cycle begins with conducting research and continues to evolve through product design, creating design information, producing product information, performing building design, simulation and modeling, and generating building life cycle information. The first stage of the physical life cycle is prototyping and testing a designed product. This stage is followed by manufacture and assembly, performance test, construction of the assembly, use, and end of use or new life of the product or assembly. The sustainability performance of a product is an interconnected network of the sustainability performance indicators listed in Table 6 (section 2.2.8). The two life cycles interact directly through continual flows of data and information. An essential aspect of this model is its systems thinking approach to product life cycle and sustainability performance.

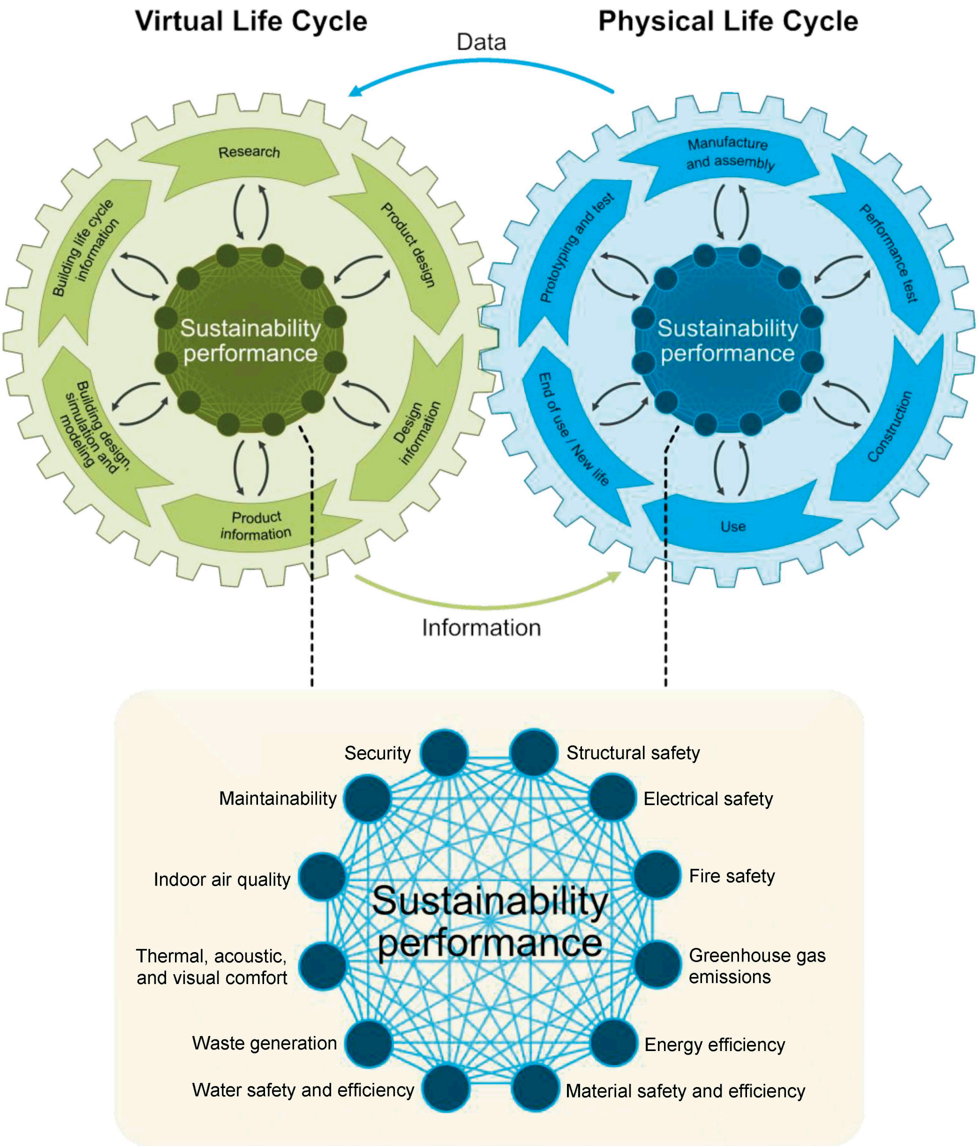


**Figure 19.** A conceptual model of product information for sustainable design and construction

## 5.3 Directions for Further Research

The development of digital twins appears to be a solution to the existing limitations of product information. However, at the time of this research work, it has not been used in building design because of technological constraints. Therefore, future research on this topic is recommended.

One of the identified problems in this research is that the fragmentation of design processes during construction projects can lead to hazardous design defects. Further research is needed on the effectiveness of the procurement methods, particularly concerning the transition towards industrialized construction. Regarding production orientation in industrialized construction, it is crucial to investigate active collaboration and exchange of information between product design and building design professionals.

Another critical area that needs further research is the professional expertise that is required for sustainable product and building design. Research on this topic could explore how to provide design teams with knowledge and skills that are required for effective use of information in design for sustainability.

Finally, as mentioned in section 2.2.5, the European Union has aimed to regulate the provision of construction product information since 1989. The identified problems in this research imply that interdisciplinary research is required to examine the mechanisms of implementing the European Union construction products regulation.

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