

Conceptual Operational Model of Architecture:
An approach for capturing values in architectural practices based on
***Big Data* capabilities**

By

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To my parents

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Abstract

The research focuses on the emerging domain of *Big Data* and the *Internet of Things* in the context of architectural design and operation. The profession of architecture relies on the use of data in almost all stages of the building cycle. However, this data is often utilised in a trivial manner, without clearly addressing how the data is utilised, when it is utilised, the value of such utilisation and the impact the data has on the design operations and the overall building. Data in architecture mainly serves as a medium of communication to generate a design. Data can only be as good as the technology available at the time it is gathered. Nevertheless, the role of data has changed with the advancement of digital data technologies such as *Big Data* and the *Internet of Things*. Digital data is now a driver for businesses and operations in other industries. The investigation of contemporary data utilisation in architecture design reveals that data is not utilised as a driver for the design in most cases and, when it is utilised as a driver, it is not exploited and is not explicitly addressed as part of the business.

A knowledge gap in architecture in addressing the utilisation of data and addressing digital data as a driver in design operations is identified. This identification is supplemented by observing that data-driven operations provide the potential for better and more efficient design and business. To fill this knowledge gap and to build a foundation for data utilisation in architecture, this thesis proposes a Data-Driven Operational Framework for architecture, which is the main output of this research and its main contribution to knowledge. The Data-Driven Operational Framework reveals and explains the required components and operations for employing a data-driven design approach in architectural processes and business. In order to develop such a framework, an investigation of current architectural cases that utilise digital data was completed, which is a crucial part of the research. However, it was not possible to investigate these cases without having a thorough understanding of the state-of-the-art data technologies and an understanding of the existing taxonomy of data and the existing taxonomy of value in architectural operations. To build this taxonomy of data, a literature review investigating the terms data, digital data operations, *Big Data* and the *Internet of Things* was conducted. To build the taxonomy of value, a literature review of values, value creation and valuation methods in architecture was performed. Also, this value

investigation led to the development of a Digital Value Equaliser, which is a conceptual representation that supports the analysis of values in architectural design cases.

The case studies were analysed following the coding techniques of Grounded Theory Methodology. The coding procedures were followed systematically and continuously until data saturation was reached. Reaching data saturation led to the development of the Data-Driven Operational Framework for architecture.

The Data-Driven Operational Framework has two theoretical applications, the Data-Driven Levels in architectural operations framework and the Data-Driven Impact on the AEC framework. These two theoretical frameworks are the findings of the second part of the research and add to the research contribution. The Data-Driven Levels framework reveals the different automation levels in utilising data in architectural operations. This framework classifies data operations in architecture into six levels according to how automated they are and the degree of human involvement in each operation. The Data-Driven Impact framework shows the anticipated impact of employing data-driven operations on the existing business and cultural models in architecture, engineering and construction (AEC). This shows the required business and cultural changes in operating an architecture business. The Impact framework supports architects to identify what measures and changes are needed to benefit from the use of data-driven operations in their practices and business.

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Acronyms

3D	Three-dimensional
AEC	Architecture, Engineering and Construction
API	Application Programming Interface
BIM	Building Information Modelling
CCTV	Closed-Circuit Television
CAD	Computer Aided Design
CNC	Computer Numerical Control
DDBM	Data-Driven Business Models
DIKW	Data, Information, Knowledge and Wisdom
FEM	Finite Element Method
FICM	Facilities Inventory and Classification Manual
FOIA	Freedom of Information Act
GIS	Geographical Information Systems
GPS	Global Positioning System
GUI	Graphical User Interface
IFC	Industry Foundation Classes
ICT	Information and Communications Technology
ID	Identifier
IOT	Internet of Things
IT	Information Technology
IP	Internet Protocol
NURBS	Non-Uniform Rational Basis Spline
PFI	Private Finance Initiative
POE	Post Occupancy Evaluation
RFID	Radio Frequency Identification
RIBA	Royal Institute of British Architects
RGB	Red, Green and Blue Colour Model
SSM	Sculptured Surface Modelling
UWB	Ultra-Wide Band
WLAN	Wireless Local Area Network
XML	Extensible Mark-up Language

Chapter 1: Introduction

This PhD thesis highlights the need for new design operations and business strategies to emerge in architectural practice as a response to the current advancement of data and information technologies. This advancement of data technology is a result of the ubiquity of computing and the immense generation and integration of digital data into architectural design. Current data technologies open new possibilities and opportunities for businesses (Minelli, Chambers and Dhiraj, 2012), and architecture as a sector has an opportunity to make the most of this and transform the profession.

Data in the digital age is exponentially growing; all new technologies are producing vast amounts of data, which includes data derived from the internet, social media, cloud computing and mobile technologies. This vast amount of data is frequently associated with the two terms '*Big Data*' and the '*Internet of Things*' (Stackowiak et al., 2015). *Big Data* technology and the *Internet of Things* have a high business potential for the architecture, engineering and construction (AEC) industry (Simpson, 2013). Analysing data using the appropriate methods provides tremendous business benefits and expands value acquisition and delivery (Yu and Guo, 2016). Many sectors, such as finance, health and information technology (IT) have already experienced these benefits. However, the architecture, engineering and construction sector has not progressed in utilising data technologies as significantly as other sectors (Bilal et al., 2016, p. 518).

Architects and designers have experienced the use of certain types of data in their profession, but these data approaches are different from *Big Data* methods. Examples are architectural surveys and post-occupancy evaluation, where both methods are based on collecting and analysing certain types of data. These methods of collecting and utilising data are usually conducted in isolation from other design operations by architects or surveyors, data in these methods is operated manually and data collection ends when the results are obtained. Another example of using data in architecture is the use of geometric data represented in two-dimensional (2D) and three-dimensional (3D) information. One use of the geometric data in the design process is Building Information Modelling (BIM), which is a process that

focuses on utilising a shared 3D model of a building. However, despite the current level of data utilisation, architects have not reached the peak of data implementation (Sailer, Pomeroy and Haslem, 2015; Marr, 2016), and the architecture and construction industry is among the least digitised industries (Manyika et al., 2015). This insufficiency in data utilisation mainly results from two factors: the first is the lack of knowledge and skills regarding data's full capacity, operational models and the values associated with it; the second is the cost of the resources involved, including time (Sailer, Pomeroy and Haslem, 2015; Deautch, 2016). However, a data-driven approach does not suggest the need to turn architects and designers into data scientists but to make them aware of their potential and value, in addition to making them capable of implementing data-driven approaches in their firms.

1.1. Hypothesis Formulation

To formulate the hypothesis, a discussion of the following three arguments are accomplished: The first is addressing technology as a change factor in architecture. The second is addressing the changes in architectural value systems. The third is discussing the architectural service from the process point of view. The connection between the three points are established, and this connection suggests data-driven operations as an answer and a potential solution for the discussed issues of acquiring value. Finally, a discussion of this research's position whereby architecture is seen not only as a "product" but equally as a "business" is presented.

1.1.1. Technology as a Change Factor in Architecture

Technology and technological advancement are affecting and changing how the AEC industry operates (Grobman, 2008; Picon, 2010; Riccobono and Pellitteri, 2014). This change can be identified clearly in the design workflows in architecture; according to Fusell, Beazley and Aranda-Mena (2007), architecture has moved from manual and CAD-based design workflow to intelligent and 3D-based processes operated in isolation for each discipline. However, the improvement of digital communications permits collaboration in design workflows between different disciplines through the sharing of models and information. The availability of internet and networking technologies allows servers to host models and share designs, providing higher integration and wider collaboration in the design workflow and process. Figure 1 shows the described change in architecture.

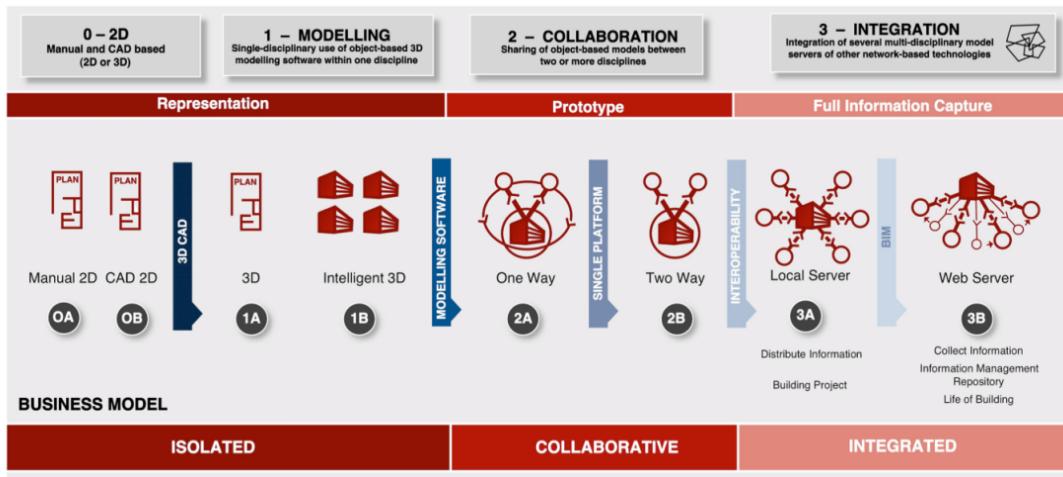


Figure 1 Integration in Architectural Business Models (Fusell, Beazley and Aranda-Mena, 2007).

This new way of working towards a culture of digital integration and shared servers allows a multidisciplinary approach to design and more implementation of data and information (Marble, 2013; Isikdag, 2015). BIM and its descendants such as Open BIM and BIM 2.0 (Isikdag, 2015) are examples of more data being implemented into the BIM model. As more data is implemented, it becomes possible to reach out to other data sources and technologies. Artificial Intelligence, *Internet of Things*, Cloud Data Management and Augmented Reality are the latest technologies with a large impact on the current architectural design processes. These technologies impact the design by expanding the industry's data sources, data implementation capabilities, design collaboration and visualisation, and this affects the service. However, the answer to the question "How can architects reach out to other data and information sources?" is not clear, along with the impact of such an approach on the architectural service and design.

1.1.2. The Change in Value Systems in Architecture

What is deemed as value in architecture is changing (Saunders, 2007). This change is affecting the value of architectural buildings and designs (Flowers, 2014). And this affects the value of architects in the design process (Samuel, 2014).

There is a concentration on the economic value of the built environment (Adams & Tiesdell, 2013). Ruth Reed, the former president of RIBA, indicated in a report: "There is a danger that in the rush to cut costs we lose more than money from our

building projects. To avoid diminishing the quality of life that good design brings, it is necessary to identify the value created by thoughtful and responsive architecture." (RIBA, 2011, p. 1). As the previous testimonial states, value has more to give than merely cutting costs, and focusing on the economic value, which is concerned with cost, might reduce the quality of the building or even increase the costs over a long period of time. Some clients might focus on cutting costs and make that a primary project requirement; other clients have other requirements. Architects role is to understand the client specific requirements and provide a design that fulfil their needs. However, Architects have been misjudged and accused of being unable to meet their clients' requirements (Gerber and Lemermeyer, 2012). "Austerity and the focus on cost have diminished trust in the value of architects' work" (Client and Architect, developing the essential relationship, 2015, p. 15). Thus, architects need to demonstrate an awareness of how to create and deliver value. Also, they are required to communicate this value to clients clearly, as there is a claim that the language that architects speak is not understood by the public (Bingler and Pedersen, 2014). A recent research claimed that architects are undervalued because there is no clear definition about what they do (Samuel, 2014). The same research concluded that architecture as a profession is opaque because it contains several conflicting value systems. Understanding these different value systems and how they are associated and contribute to the design process in architecture is essential for understanding the data contribution to a design project.

1.1.3. The Change in Architectural Services

Technology as a changing factor and Value as an aspect of that change should have a clear influence on the design process and the service. Yet, it is not clear how this influence should affect the quality of architectural service. However, according to a recent survey carried out by the Architects Journal, 72% of 50 local developers stated that architects' service had either got worse or remained the same over the past few years (Waite, 2012). This study reveals unexpected results. If the service is not developing, then the business will suffer and fall behind, and this will affect the architects and their role in the construction industry. This role has also been questioned: in 2015, RIBA published a report titled "The Future of Architects?" This report listed the types of practices which are anticipated to remain stable during a recession in the profession. One of these types is "Traditional Regional

Delivery Driven Practices" (Robinson, Jamieson and Worthington, 2009). The report defined these practices by their ability to provide process-driven services to attract clients who have low interest in design as a vocation. This definition suggests broadening the approaches of architectural practice beyond design as a vocation and seeking new process-driven approaches. Also, clients are becoming more interested in seeing the effectiveness of the design; they increasingly expect architects to provide evidence of the competence and effectiveness of their designs (RIBA, 2015).

The change in the service, the recession in the profession and the increase expectation of clients suggests a move in the architectural profession to a process driven by data. This approach could provide a solution to meet clients' needs and could clearly demonstrate the actual role of architects and their value contribution. A Data-Driven design approach offers this opportunity through delivering an evidence-informed design by utilising data. However, there is a need to further investigate Data-Driven solutions and how they are implemented in the design process (Bilal et al., 2016; Deutsch, 2015; Barista, 2014).

1.1.4. Architecture as a Business

"Architecture is not an inspirational business, it's a rational procedure to do sensible and hopefully beautiful things; that's all." Herry Seidler

There is often conflict between architects when referring to the profession as a business since some architects do not consider architecture to be a business (Jamieson, 2011). On the other hand, being a good architect is not enough for a business to succeed (RIBA, 2014), and this makes architecture a business, and architects in need of business and management skills despite the disagreement and disapproval. There is no contradiction between architecture being a business that employs operational models and architecture being a vocation that addresses social aspects through the design of buildings and structures.

In 2014, the RIBA Benchmarking Executive summary clearly stated that "business planning remains an anathema to many RIBA Chartered Practices, particularly the smaller ones" (RIBA, 2014, p. 1). The same report indicated that only 60% of the

practices in the benchmarking survey had a business plan. Architects are not directly educated to be businesspeople, as their education focuses more on “the design”. The language of business and business planning is not part of their mentorship and education. Thus, their focused approach on the design makes them captivated by the design procedure and the commodity. Nevertheless, incorporating a business outlook might enhance their procedure and enable them to provide a better service. Focusing on the service rather than the commodity is one approach to change the way architectural firms operate.

The Business of Architecture website raises the awareness of architecture as a business in an useful way which conveys different schemes, tools and strategies to outreach the procedure and the profession (Business of Architecture, 2013).

In business, talking the language of the clients and being able to communicate with them effectively is essential for success. Clients are interested in the value of the service they are receiving; they need to see evidence and proof. This can be clearly conveyed by presenting them with data. The same is applicable in the architecture and construction field. Occupants and owners are always looking for better services, more concrete solutions and innovative results, and this requires architects to be aware of emergent technologies and advanced services. This technological advancement matches one of the key visions in the 2025 construction industry report (Betts et al., 2013). This consideration for architecture from a business perspective will be followed throughout this thesis. This research does not criticise or contradict the way architects currently operate, but it provides emerging operational models and methods from other domains which the architecture business could employ.

1.2. Related Work

At the time this research began, in 2013, there had not been many studies concerning *Big Data* or Data-Driven Design in architecture as a business. Nevertheless, some non-academic articles had been written in various blogs and online platforms highlighting *Big Data* as an approach in design and construction. For example, Simpson (2013) wrote an article in the Design Intelligence journal titled: “The Power of *Big Data/Big Design*”. This article is one of the motivational

pieces for this research. In it, Simpson listed hypothetical scenarios for what *Big Data* could bring to the industry of design and construction. He argued that the advent of *Big Data* in the current inefficient industry should be welcomed (Simpson, 2013). These mentioned scenarios are based on his particular understanding of *Big Data*, and they could happen in the future. Simpson ended the article by questioning the design community's acceptance of such technology or approach. This ending emphasises that the problem lies in the society's current practices. This might be part of the dilemma: that architects are prone to avoiding a change in their profession. The majority of the dilemma lies in not understanding how to operate this technology and the value in using it, and this is one of the issues which this research is trying to tackle and to clarify.

Academic research and articles have been published to inform some data-driven approaches. Mario Carpo has an interesting understanding of what *Big Data* is bringing to architecture from a historical perspective in his article “Breaking the Curve: *Big Data* and Design” (2014). Moreover, Carpo (2015) referred to one data-driven approach as “The New Science of Form-Searching”. Bader, Kolb, Weaver and Oxman (2016) discussed data-driven material modelling for 3D fabrication. The mentioned research focuses on one aspect of the potential of these data-driven approaches, and most of them are not aiming at addressing the architectural business aspect of the process. However, the list is expanding as more researchers are taking an interest in this field.

In 2016, a book titled “Data-Driven Design and Construction” (Deautch, 2016) was published. This book is considered one of the first published books, if not the first, with the aim of providing the industry of architecture, engineering and construction with a basic understanding of data implementation and data-driven approaches. Although the book is considered an extensive and a novel research effort, it has some limitations. According to Khemlani (2016), whilst the book is packed with interviews with practitioners and researchers who utilise data in an innovative way, it lacks any case studies where data was used efficiently, or a description of how it made a difference to the business or the process. Moreover, while the book’s title contains the phrase “25 Strategies for Capturing, Analysing and Applying Building Data”, it needed to present actual action-oriented strategies or how-to suggestions

for the business or the process. While this book has only recently been released, and there was no prior information regarding its content, it is a fortunate coincidence that this research is addressing these mentioned shortages and attempting to clarify some of the obscurities regarding data and data-driven strategies focusing on architecture.

Another research area with which this thesis connects is the developments in the field of “future cities and smart cities”. Smart cities frameworks and models were developed with the intention of enabling businesses and governments to utilise technology and data effectively in cities (The British Standards Institution, 2014; Falconer and Mitchell, 2012). Three main points distinguish this research approach from other “Smart Cities” research. The first is the scale and the peculiarity of data and operational models. This research focuses mainly on data in the process of architectural design and business, while future cities frameworks apply models to the whole cities with no specification or details regarding the business or the process. The second is assessing data and technology from the “value” perspective. The research specifies data-driven values in the built environment from the architectural perspective while smart cities frameworks focus on the stakeholders and process. And, lastly, this research focuses on the data aspects and application while the future cities framework has different urban themes such as resilience and sustainability (Cavada, Hunt and Rogers, 2014). This research contributes to bridging the frameworks’ gap between data in a building and data in a city by redefining an area of operations that allows the understanding of the different levels of data integration.

1.3. Research Aim and Objectives

The research aims to explore a new method of integrating data into the design and related operations in architecture and the emerging value propositions that arise from such integration. This focus is on the three aspects of architectural design: the design operations, the value generation and the link between the two. These three aspects are investigated under the influence of new data technologies such as *Big Data* and the *Internet of Things*. Since these data technologies have not been clearly identified in architecture, it is necessary to establish a foundation for the knowledge and an understanding of each term. To achieve this, there is a need for an

architectural Data-Driven Operational Framework to clarify the data operation in architecture and support digital value creation in the business.

The aim is achieved through the following objectives:

- Identify the definition and the possible use of *Big Data* in architectural businesses to capture its potential.
- Investigate value in the built environment in order to assess how data technologies contribute to new value creation.
- Critically assess and analyse existing cases that present efforts to integrate data through the design process in order to understand current methods, technologies and values.
- Define the main components of data-driven operational models that exist in other industries and contexts; and transfer these components into architectural practice.
- Develop a data-driven operational framework for architectural practice which assists data integration as part of the design and supports data-driven business models with clearer value implementation.

1.4. Research Scope

The research is conducted from an architectural perspective focusing on the operational models of design in a business context. Operational models in architecture are the business processes and activities that architects employ to provide and assess their design and service. Operational models encompass the resources and procedures involved in developing the design and offering the service. In this research, the investigated resource is data and particularly digital data; this investigation covers the digital data procedures. However, the research will not cover other aspects of the business such as business partners, business channels, cost structure and revenue streams due to the time limitations and the complexity of data activities.

The implementation of data-driven approaches is not exclusive to one industry; this is because data-driven technologies promote a culture of integration and enable the contribution of other stakeholders and industries (Elgendi and Elragal, 2014).

Figure 2 shows how the research scope is positioned in relation to other sectors. The research scope is highlighted in dark grey. The research is positioned in the architecture, engineering, construction and operation domain with a greater focus on architecture. The main concern of the research is the operational model with a focus on value contribution.

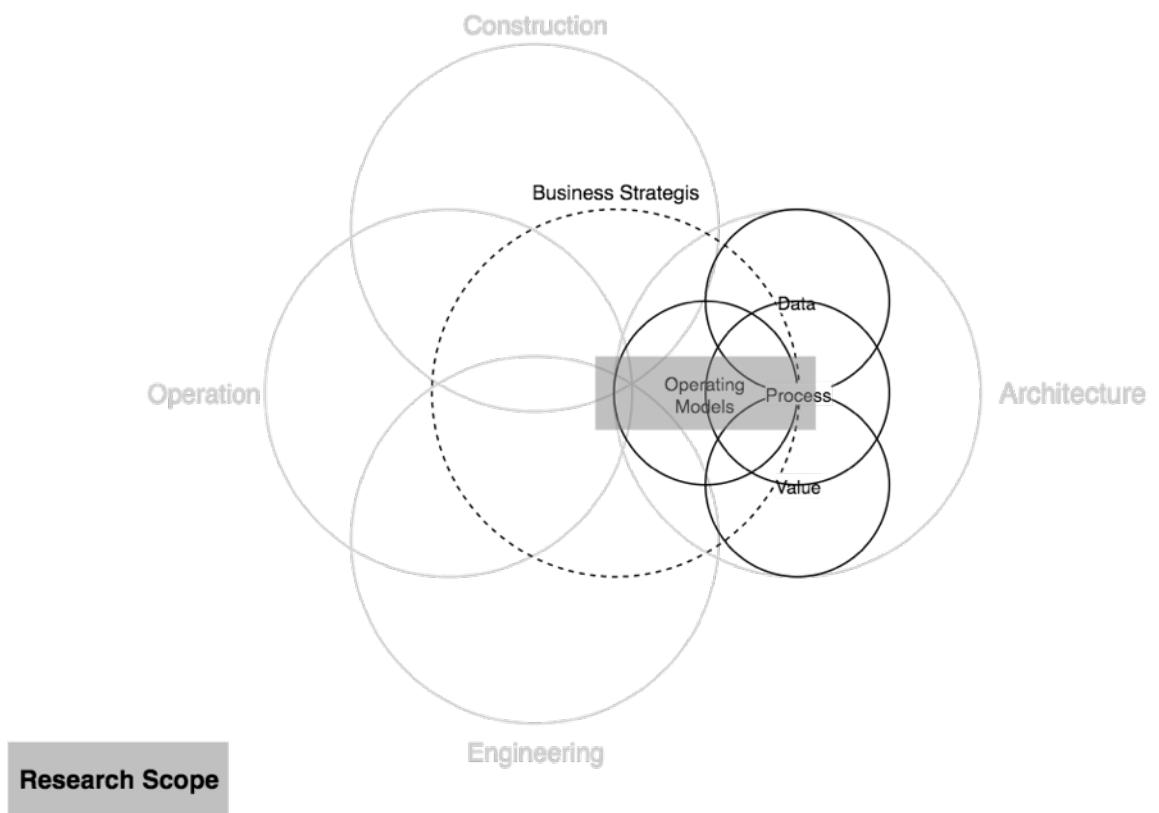


Figure 2 Research Scope Diagram

The figure demonstrates a conceptualisation organisational chart of the different units (Architecture, Construction, Operation and Engineering) that form the building process and lifecycle. Each of these units has its subunits. In architecture, the subunits that are related to the research are Data, Design Process, Value and Operational Models. Each unit (Architecture, Engineering, Construction and Operation) has an Operational Models subunit. The Operational Models of all units together define the business strategies of a company or practice. The focus is on the architecture operational models that emerge from the design process that is utilising the Data and Value subunits.

1.5. Research Methodology and Data Collection

Various types of data are collected through the research. A theoretical review of literature was conducted to provide the knowledge foundation of the thesis. The literature covers several subjects that contribute together to achieving the objectives. The literature review for the first objective focused on materials on data, data in architecture, digital technology in architecture design and *Big Data*. the literature review for the second objective focused on value and valuation methods.

Case studies were the primary source of data. Case studies were collected and an initial comparison was completed for selection purposes. The case studies are analysed following a Grounded Theory approach for coding and analysing data with the aim of generating a theory. Grounded Theory is defined as a general method that is based on a systematic generation of theory from a systematic research approach. It is a set of accurate research methods leading to the development of conceptual categories and classes (Glaser, 2014).

The Grounded Theory requires an initial research question to focus the attention upon a particular phenomenon that is desired to be investigated (Willig, 2013). The question aims to guide the Grounded Theory analysis and not propose an assumption about the phenomenon. The question that initiated this analysis is: “How can architectural businesses apply a data-driven approach to acquire more value in the built environment and possibly change the profits standard?”. This question guided the analysis and proposed a hypothesis.

The Grounded Theory coding in this research was chosen for the following two reasons: first, Grounded Theory enables theory discovery in the data and abandons previous assumptions made in the field of study (Corbin and Strauss, 2008); second, Grounded Theory is useful for research in areas that have not been sufficiently studied or where a new understanding is required (Schreiber et al., 2001). In this research, the studied theory (Data-Driven Operations in Architecture Business) is under-researched, which led to the utilisation of the case studies for theory discovery, in order to understand the data-driven operations.

A Straussian instead of a Glaserian approach of Grounded Theory was followed for two reasons (Muller, 2010): the first is that the Straussian approach allows the literature review to direct the theoretical sampling and supports the concept development. In this research, the conducted literature review about Value and Data was utilised to direct the initial theoretical sampling and coding process of the case studies. The second is that the Straussian Grounded Theory has improved structured data analysis and coding, which is executed in three phases: Open, Axial and Selective. This coding is more suitable for the studied cases in this research because the case studies vary in their data-driven application, and having a systematic coding provides better control of the analysis and the analysis results.

The literature review aimed to guide the coding and establish initial categories for analysing the case studies and considering the process of data-driven designs. The literature review originates from two sources. The first is the value systems that are associated with architecture and the built environment; the aim of this review is to allow an understanding of how data and value are correlated in the context of this research. A "Value Theory" approach was followed to examine this available literature. The second source of literature is borrowed from the Information Technology field. The "Borrowing Theory" allows appropriation of the available literature; the aim of this review is to study existing data-driven processes and form an understanding of their implementation in architecture and the built environment. Some of the literature is included as a secondary source of the collected data. Grounded theory is compatible with a wide range of data collection techniques. Thus, it was possible to collect data and utilise various theories in the data collection phase.

The main source of collected data is the case studies. They enable the investigation of data-driven applications within the context of architecture and design. A continuous comparative analysis for the studied cases was carried out to cover the contextual conditions that are relevant in the realm of data-driven design in architecture and the built environment. The Grounded Theory enables a comparative, case-oriented and explanatory methodology for the case study. The aim of analysing the case studies is to build an understanding for existing business operations and models.

Each coding phase had a specific objective. The Open Coding delivers categories for the data-driven model in each case; the observed phenomenon is the use of *Big Data* technologies. The Axial Coding delivers dimensions, concepts and assemblies by relating the established categories to the sub-categories through all the cases. The Selective Coding integrates the categories into the proposed framework. These three types of coding were not employed in sequence; in fact, the process was overlapping and a continuous cycle of moving between the collected data, the analysis and the insights took place – a pattern of constant comparative analysis.

1.6. Expected Research Outputs

The research proposes a taxonomy of the components of data-driven design operations in architecture and the built environment. The relationship between these components provides an understanding of various architecture data-driven models and processes. This understanding allows the creation of a general framework of data implementation and application in architecture. The framework proposes a different level of automation in utilising data in architecture. Finally, the impacts of such operations on current business models have been evaluated.

1.7. Thesis Overview

The thesis consists of six chapters. Chapter 1 (Introduction) contextualises the research's approach taking in the problem and solution formulations. The chapter identifies the aim and objectives, defines the research scope and provides an overview of the thesis.

Chapter 2 (*Big Data* and Architecture) establishes a basic understanding of the terms *Big Data* and the *Internet of Things* as used and interpreted by this research in the analysis of the case studies in Chapter 4. Hence, the chapter discusses what data implies in the context of architecture, and how the evolution of digital technologies in architecture contributes to this understanding. This discussion is followed by defining the technology of *Big Data* and the *Internet of Things*, which leads to a discussion of *Big Data* and the *Internet of Things* in business and data-driven business models. These business models provide initial categories of data operations

that are utilised in the case studies analysis in Chapter 4. Finally, the chapter discusses the challenges and opportunities of data-driven technologies in architecture.

Chapter 3 (Value in Architecture Design) aims to build an understanding of the correlation between value, value creation and data in architecture and the built environment. A thorough review regarding values, value taxonomies and value systems in architecture is conducted. This review is followed by an analysis of current valuation methods in the built environment. The chapter identifies a new definition for Digital Value in architecture and develops the Digital Value Equaliser tool to be used in the analysis of case studies in Chapter 4.

Chapter 4 (Case Studies) analyses eight cases based on the themes identified in previous chapters: Data Sources, Data Handling, Data Offering, Architectural Value Proposition, and Architectural Business Channels. The chapter aims to extract the Data Operation of each case and reveal the implemented Digital Value using the concept of the Digital Value Equaliser.

Chapter 5 (The Development of the Data-Driven Operational Framework) provides in-depth coding and analyses (Open, Axial and Selection) of the data collected in previous chapters. Based on these analyses, a theoretical framework for the Data-Driven Operational Model is developed. This model allows an understanding of the different autonomous levels in utilising data in architecture which leads to the proposition of a framework for Data Operational Levels. Finally, the chapter presents the impact of data-driven operations on the existing business and cultural models in architecture, engineering and construction, and identifies potential future changes.

Chapter 6 (Conclusion) summarises the main findings. The chapter provides recommendations for future research and highlights the thesis's contributions to research, practice and education.

The following diagram shows how each research objective corresponds to the different chapters in the thesis (Figure 3).

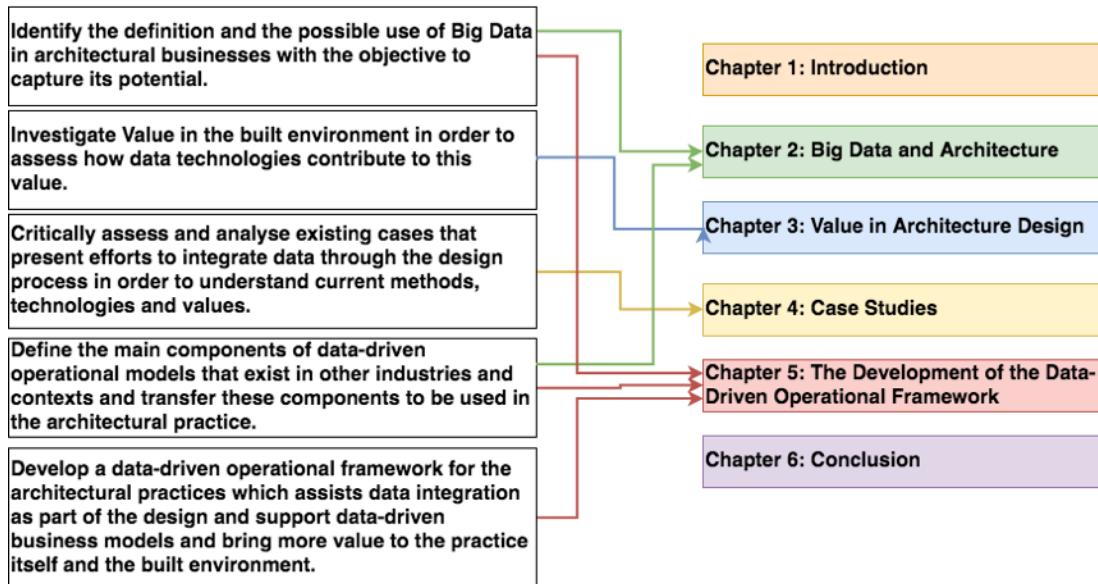


Figure 3 Research Objectives in Relation to Chapters

Chapter 2: *Big Data* and Architecture

“Data is the new oil,” Shiven Zilis

This chapter introduces the concept of *Big Data* and the *Internet of Things* (IOT) and indicates the significance of *Big Data* and the IOT technologies in comparison to other data technologies for architecture and the built environment. The chapter explores the potential impacts of *Big Data* and the IOT on architectural design and business. The aim of this introduction and indication is to construct a foundation in support of the explanation of terms, potential and values related to the associated data technology. The investigation is carried out based on the application of this technology in architecture and the built environment from the design operation perspective. Additionally, this chapter provides a thorough understanding of different data uses in architecture.

The chapter is structured to achieve the following three objectives. The first is to provide a thorough understanding of data definitions and uses in architecture. To establish this, a review of the definition of data, information and knowledge is undertaken to understand how these terms are positioned with relevance to design operation; this review leads to the interpretation of the term data in the design operation. Then, data types are examined and data in architecture is investigated from three architectural perspectives: ideology, profession and service, in order to differentiate what data means to architecture. These three perspectives were realised based on a thorough analysis of precedents. Investigating data from these three perspectives clarifies the role of data and highlights its value.

The second is to provide an understanding of the relevance between data and digital computation in architectural design and highlight the recent technologies and how they contribute to the current data revolution. This is achieved by investigating the emergence of digital operations into architectural design and the role of architects in this emergence.

The third is to establish basic themes to be utilised in the coding and analysis of the case studies. These themes are adopted from other data-driven sectors and

specifically the field of Information Technology. The reason for reaching out to the IT sector is because it is one of the sectors that have the highest value potential for the utilisation of *Big Data* and the *Internet of Things* in business (Manyika et al., 2011). The third objective is achieved through defining *Big Data* and the *Internet of Things*, and examining the digital processes and terms associated with data. This leads to the identification of existing data-driven business models. These data-driven business models are investigated with the aim of extracting the data operations and utilising them in the analysis of the case studies (Chapter 4).

2.1. Data in Architecture

2.1.1. Data, Information and Knowledge

Data and Information are often used interchangeably to convey knowledge (Doyle, 2014). Understanding the correlation of these terms (data information and knowledge) allows an understanding of the process of transforming data into information and knowledge. There are many definitions of Data, Information and Knowledge. For example, Zins (2007) documented 130 definitions formulated by 45 scholars in his article "Conceptual Approaches for Defining Data, Information, and Knowledge". In the following paragraphs, a discussion about Data, Information and Knowledge is presented to build an understanding of the terms through reviewing and examining definitions and then representing them in the current context of architecture.

Data as a word is derived from the Latin word "datum", which means "that which is given" (Mahoney, 2002). Data are values assigned to objects, expressions, functions and properties, where these values do not provide a complete description, but are necessary elements (Wellisch, 1996). Data is raw, unshaped, unprocessed and uninterpreted, and alone is not meaningful or informative. According to Schmitt (2015), Data is the smallest entities of Information. This definition indicates that Data represents the initial components for creating Information. Defining data through Information requires defining Information. Information is derived from the Latin word "informo", which means to "form an idea of" or "give a shape" (Mahoney, 2002). When sets of data are collected and processed, data is transformed into information. Information is sets of related, connected and

contextualised data that is meaningful to humans (Liew, 2007). Information provides an abstracted description of reality. It can be defined as a message which is communicated through visuals and audios (Davenport and Prusak, 1998). Information is associated with two characteristics: share-ability (Freyd, 2003) and relations (Liew, 2007). Information communicates connected data in a meaningful way to trigger an insight in the receiver. If the receiver experiences an insight, this experience is referred to as Knowledge (Kelley, 2002).

According to Kelly (2002), Knowledge is an insight which is experienced after receiving information. This definition constructs Knowledge as actionable information that emerges through experience (Alavi & Tiwana, 2013). Knowledge is also defined as data and information that has expert opinions, skills, and experiences, of which result in a valuable asset that can be used to aid decision making (Chaffey & Wood, 2005). These definitions place knowledge as perception and an understanding that is happening in the human mind. However, this proposes three issues; the first is the time of which this understanding happens, the second is the cognitive capability of the perceiving human's mind, the third is the source of information of which the knowledge is built. These three issues can vastly change what is considered Knowledge. A relative definition is that Knowledge can be defined as the current collective understanding of information regarding a problem or situation or context. Another definition is that Knowledge at any given moment is a function of the inceptions of the available means of perception (Bateson, 1979). These definitions reveal Knowledge as a complex multi-perspective understanding. The Gettier Problem represents a philosophical problem for the understanding of the multi-faced of knowledge as it challenges the Justified True Belief presented by Plato as an account of knowledge.

The previous definitions form a hierarchy for Data, Information and Knowledge. This hierarchy can be seen in the DIKW Pyramaid. The DIKW (Data, Information, Knowledge, Wisdom) pyramid is widely used to describe the relationship between Data, Information, Knowledge and Wisdom in cognitive psychology. The pyramid represents the transformation of Data in acquisition to Information in processing, then to Knowledge in interpretation and finally Wisdom in application. Wisdom appears at the top of the pyramid. Wisdom is considered the ultimate level of understanding; it is acquired when the knowledge base reaches a saturation level of

patterns that can inform future decisions. This synthesis of knowledge patterns allows novel interpretation, assessment and prediction of new use patterns. Figure 4 shows the DIKW pyramid and how data, information, knowledge and wisdom are placed in relation to each other.

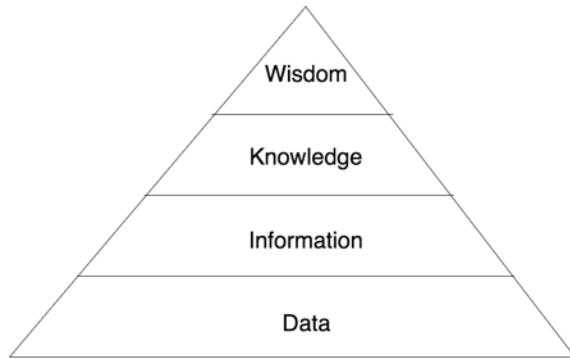


Figure 4 The Widely Used DIKW Pyramid (De Stricker, 2014)

This understanding of Data, Information and Knowledge can be recognised in time. The recognition shows Data, Information and Knowledge as understanding of past experiences and leads to Wisdom which is a future novelty (Hey, 2004). Wisdom is a novel experience that helps the understanding of future (Algeo, 2014). This view of the DIKW is represented in Figure 5; this diagram shows the continuum of understanding in relation to the context associated with it. This understanding of Data considers it as a small unit that eventually evolves through the context to achieve Wisdom as a whole.

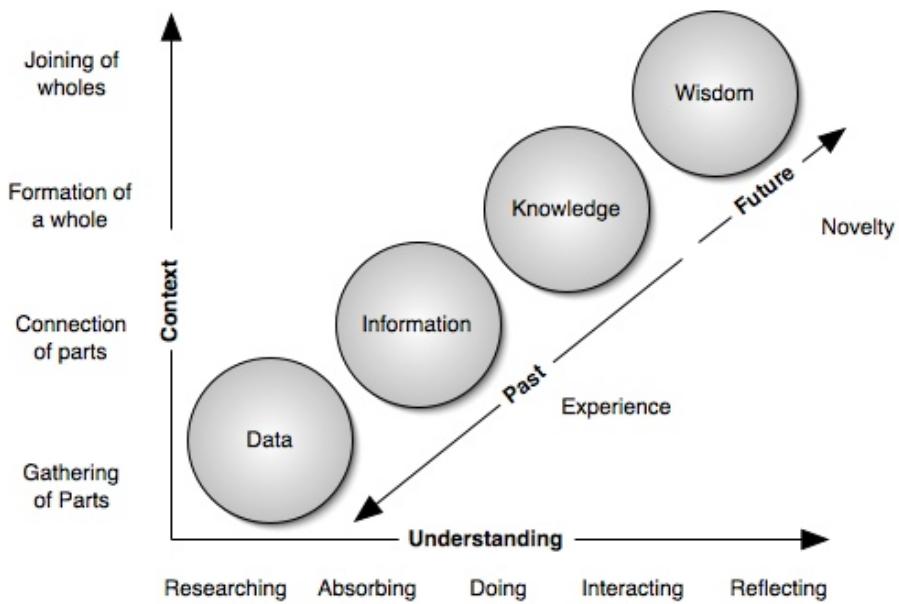


Figure 5 The Continuum of Understanding (Clark, 2004)

To contextualise the data understanding from Figure 5 in architecture, an investigation of how this understanding is related to architects is achieved. The investigation is based on mapping this understanding on the design process. To achieve this, the 5-steps model of design process proposed by Mahmoodi (2001) is utilised. The reason for choosing this model is that the model is comprehensive and compiled from various academic viewpoints on the design process. The model consists of five steps: Intent, Preparation, Proposal, Evaluation and Action. Intent is a pre-stage in the design process which affects the type of data required. Data is raw input that is collected in the preparation stage. Data is analysed, interpreted and transformed into schematic and development designs in the Proposal stage. Schematic designs are types of information given by architects. The process of evaluating these schematic designs requires testing based on previous Knowledge. Finally, an action is taken by architects through a decision that presents a solution. This mapping of Data, Information, Knowledge and Wisdom on the architectural design process shows where each of these definitions emerges in the design process.

2.1.2. Data Interpretation in Architecture

Architects rely on and are affected by different types of data in their design and decision-making process. Incorporating data into the architecture design process is not a new concept as architects have been doing that since the beginning of the

profession (Wisneski et al., 1998). Data serves as an input in the design process. It allows the architects' interpretation to connect and to transform part of the available data to applicable designs represented in space and buildings.

Ernest Neufert published the first reference book on architectural data in 1936. The book was titled "Architect's Data". Since then, many editions have been published and used by architects around the world. This handbook provides technical data resources for architects regarding the standards and spatial requirements of the different aspect of buildings (Neufert and Thackara, 1980). Architectural data in these types of books have different categories. Adler (1999) listed the basic design data categories as: Anthropometric, Ergonomics, Circulation spaces, Activities, Furniture and Storage. Buxton (2015) classified design data as: Design information and dimensional coordination, People and space, People and movement, Access and inclusion, Capital and whole life cycle of buildings. However, this data is numerical and provides dimensions that set initial guidelines to architects. Data of this type is standard for all architects from any background or time. This data is abstracted and detached from any relations or representations. It aids architects' design decisions and supports their thinking. The resource of such data is inherited in the tradition of the profession. Implementing this technical data in architectural design makes the process data-informed, which is different from data-driven, as what drives the design is the architect's implicit essence (Fiscus, 2012). Technical data aids architects in the design process, allowing them to take design decisions based on intuition and implicit reasoning. Architects rely on their intuition and that creates their creative impulse (Linzey, 1998). This intuition is intangible and not observed but can be partially described. Intuition is a subjective evaluation of patterns and relationships between various elements (Linzey, 1998). Intuition determines the difference in the design artefact and process between different architects even when utilising the same data. For this intuition to happen, there is a need for data to start with. And more available data supports wider utilisation. However, data interpretation makes all the difference. Data interpretation in architecture is not only affected by the architect's intuition as clients and end-users might affect this interpretation.

According to Deutsch (2015), the decision-making spectrum in architecture is

Subjective or Objective based on the input type. Taking design decisions based on quantifiable data is considered an objective approach while taking design decisions based on unquantifiable data is subjective. The subjective approach is based on intuition and emotions. However, other factors also contribute to how architects make decisions. Figure 6 shows the continuum of decision-making proposed by Deutsch (2015).



Figure 6 Decision Making Spectrum (Deutsch, 2015)

However, this analogy and understanding is not totally accurate. The reason is that data and emotions are presented on the same level as opposing interpretations of decision making. However, data is not the opposite of emotions. On the contrary, data could allow emotions, along with other interpretations in the decision-making spectrum.

In response to Figure 6, a refined diagram (Figure 7) of the decision-making spectrum is proposed. In this diagram, data informs different interpretations which allow a decision to take place regardless of the type of interpretation. Rather than having data as opposite to emotions, data becomes the driver for allowing various interpretations; building on the given understanding in the previous section on data in the design process, data is represented as an input, and decision as an output of the interpretation process taken by architects on different levels. The reason for focusing on the decision is because it is a simple action that results from an architect's interpretation of data.

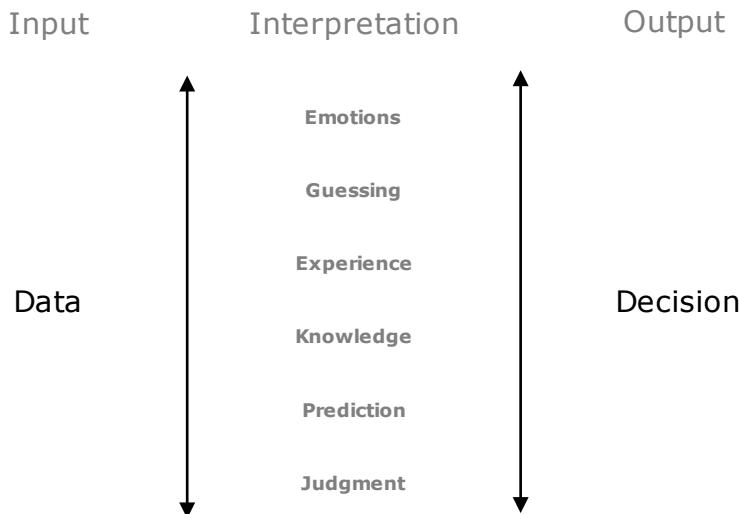


Figure 7 The Refined Decision-Making Spectrum

According to the previous discussion, data is a representation of the smallest unit in the complexity of design knowledge. Data is an input. It is a transmittable component of design knowledge and the input for all processes. The definition of data in architecture is not conclusive, and how data is defined is not important. What is more important is how data is employed and interpreted and this makes the whole difference. Identifying the intent behind data use and the interpretation method is fundamental for effective data use.

2.1.3. Types of Data in Architecture

This section aims to map and to clarify what types of data architects employ. There are different perspectives on determining data types in architecture. In this section, data classification based on four aspects are presented: Quantification, Format, Time and Perception. The reason for introducing these classification approaches is to provide an understanding of data types and terminologies that are currently used in the architectural design process. Data types affect how data is interpreted as certain types of data require certain data processes and applications. Also, this classification of data supports the case study analysis in Chapter 4 (Case Studies).

Data is either quantifiable or unquantifiable (Qualitative) based on its properties (Preiser, 2015). There is a debate regarding what data is quantifiable (Riska and Berka, 2012). Quantifiable data can be accurately estimated and quantified using measurement tools such as dimensions, numbers and readings. Architects often rely

on this type of data in producing their blueprints and in communicating their designs to engineers and builders. Quantification in architecture allows comparisons to be established between certain aspects of the design and optimum living spaces and conditions to be determined. Some aspects of the architectural spaces are quantified as they can be represented in numbers and units, such as corridor measurements and wall dimensions. This quantified data includes thermal and ventilation factors. Other properties such as living quality and spaciousness cannot be directly quantified and represented in numbers, but they can be described. Unquantified data can be sensed and demonstrated using human judgement, reasoning and emotions. Architects often use this data to explain the design concept, the quality of space and the architectural style. The advancement of data technologies and sensors in the built environment provides a new possibility for quantifying data and increases the spectrum of quantifiable data as some intangible data became tangible. An example of this is quantifying human emotions in Weber-Fechner law.

The digital revolution carried its own type of data, and data became either Digital or Analogue, based on the measurement source (Angelakis et al., 2017). Digital data is acquired by digital mediums, saved as binary digits and represented in numeric codes and values. Digital data is discreet. On the other hand, Analogue data is acquired through human skills, perception and awareness. Analogue data is continuous. Most of the processes these days operate in between these two types as digital devices are almost ubiquitous but a human presence is required. An example of this is the digital data from the 3D laser scanner in comparison to the analogue data of the traditional use of analogue tools such as rulers.

With regard to the time it is acquired, data falls into three categories: Past, Present and Future data (Redman, 2013; Dixon et al., 2018). Past data allows architects to propose solutions based on previous experience. Some of the past data is outdated and does not necessarily address current situations and contexts, but it provides a vague assumption and solutions. An example of Past data is the architectural data embedded in historical architecture and literature regarding dimensions, styles and narratives. Also any data which is collected or recorded regarding the design and operation at a certain time. Present data is recent data which enables architects to

propose designs and solutions that are suitable for current contexts and situations, for example, Topography and Climate Data. Some present data can be monitored in real time. An example of this is User Behaviour data and Energy Consumption data for buildings. Present data allows short-term solutions but does not consider future conditions. Future data is data acquired through assuming certain future scenarios and predicting the future behaviour based on past and present data. An example of this is running a thermal simulation. Architects work within these three types, varying their decisions based on their experience, value and motive.

Another classification of data is based on the perception of data through human sensory systems and media modalities; data is either Visual, Auditory or Kinaesthetic (Polovina, Priss and Hill, 2007). Visual data has different formats: schematic diagrams and visualisations. Auditory data includes sounds and noises, and Kinaesthetic data includes temperature and movements. In addition to these perceptive data, there is data based on other senses such as smell and taste.

Architects use and refer to various data formats spontaneously during the design process. Table 1 summarises the data types that are listed and shows the different categorisations. This variation of data uses is observed again when analysing the cases in Chapter 4 (Case Studies).

Table 1 Data Types

Data	Quantification	- Quantifiable - Unquantifiable
	Source	- Digital - Analogue
	Time	- Past - Present - Future
	Perception	- Visual - Auditory - Kinaesthetic - Sense of Smell - Sense of Taste

2.1.4. Data in Architecture Design as Ideology, Profession and Service

In this section, a formalisation of how data is interpreted in different architectural approaches is proposed and explained. This proposal reveals the significance of Value as a data driver in architecture regardless of the approach. An explanation of the architecture approaches is provided.

Data in architectural design has long been associated with the standard resources of technical data such as the likes of “Time-saver Standards” and the “The Architect’s Handbook”. These books provide a comprehensive range of technical information for architects regarding the standards and requirements of the different types and aspects of buildings. However, this data does not have any impact on the design unless the architect consciously searches for and applies the selected solution to the design. Data here is simply representing inputs which architects are required to connect and transform into meaningful designs (RIBA, 2013). Data is mostly understood as constraints and opportunities and relies on architects’ reasoning capabilities and intuition to influence design decisions (Hois et al., 2009)

Data and information utilisation in and for architecture reveals specific patterns according to the varying perceptions and reproductions of design: design as ideology, design as profession and design as service. Architectural design as ideology focuses on the design of forms which respond to perceived social needs with underlying theoretical assumptions (ŠUVAKOVIĆ, 2014). It goes beyond the pragmatic function of architecture and is largely associated with the cultural and ideological positions taken (by the architect). The data that drives the ideology is often qualitative, symbolic, philosophical and unquantifiable. The design process depends on the architect’s intuition, and his or her personal, ideological and subjective standpoint. Most architectural styles are ideological in their core. Design as ideology provides a system of values based on symbolic meaning.

Thinking of architecture as a profession rather than an ideology avoids its deep connection with its social, political and cultural roots, and rather focuses on the economic and market values (Symes et al., 1995). Architecture as a profession focuses more on the functional and economic value generated from its pragmatic

function. This representation of architecture is relatively contemporary and came into play with the increasing influence of capitalism (Mako, Lazar and Blagojević, 2014). Also, architecture as a profession is mostly driven by the market, which dictates its principal values and trends (De Graaf, 2015).

Architecture as a service focuses on the design process rather than the artefact (Brophy & Lewis, 2014). This perspective extends the design process to consider the overall service-life of the product (the building) including after-sales (post-occupancy). Architecture as a service sits somewhere between the previous two approaches (as profession and as ideology). Data that drives architectural design as a service usually aims to enhance the overall building performance and quality. In other words, data is aimed at improving value within the performance.

Table 2 Data in Architecture Design as Ideology, Profession and Service

Approach	Data input focus	The role of data in the process	Associated terms
Ideology	Intuition	Guidance	Symbolic
Profession	Market	Meeting markets need	Market
Service	Process	Evidence	Performance

The proposed redefinition of data in the above table (Table 2) shows that data is more than just an “input”. Its role is extended and allows other values to emerge. It becomes quite clear that value is the main objective when assessing data and that the achieved value is crucial in understanding how data could be employed. Architects implement values and evaluate their designs. These values affect their design methodology, their design and their architectural business. This discussion of values and how values affect design will be examined thoroughly in the following chapter (Chapter 3: Value in Architecture).

2.2. Architecture Digital Operations

As discussed earlier, data utilisation in design is not new for architecture and architects; what is new is the substantial digitisation of data. This digitisation depends heavily on the use of computers and technology. This use of digital

technologies in design accelerated the design process, and this promoted a digital shift in the architectural design process and workflow. Many factors caused this shift in addition to the digitisation of data. In this section, other factors such as the advancement of drawing technologies, and the relationship between architects and machines are discussed. This discussion reveals that the approach of implementing digital data-driven systems in the design exists theoretically in the history of the profession. And architects are seen as designers of systems and machines that design architecture. The discussion reveals that architectural design extends beyond the design of the building as an artefact and provides the foundation to understand the evolution of digital technologies and the effect they have on data implementation in architecture.

2.2.1. Architecture Machine

“Architecture Machine” which is derived from Le Corbusier well-known phrase is an important concept which has been often used in history as an analogy (Atmodiwirjo & Yatmo, 2016). The investigation of this analogy aims to develop an understanding of how machine understanding is incorporated within architecture and reflected in the process and the role and data.

One of the recognised uses of the term is found in Corbusier’s work. Corbusier’s ideas on how architecture should meet the demands of the machine age led him to develop his theory of purism (Johnson and Vermillion, 2016). Purism promotes simplifying the design and waiving the decorations to achieve an architecture that is efficient like a machine. This led to Corbusier’s famous description of the house: “A house is a machine for living in” (Corbusier, 1931, p. 95) and his ideas of developing standardised house types. Another use of the term “Machine” in architecture comes from Libeskind (1985). Libeskind created three large installations for engaging the public. He indicated that architecture can be created and interpreted by the public social, cultural and historical perspectives using three large machines. He argues that the three machines “propose a fundamental recollection and a retrieval of the historical destiny of architecture” (Libeskind, 1985). This fascination with the “Machine” reflects the architects’ interest in the system (Johnson and Vermillion, 2016).

Gordon Pask stated that architects design systems, not just buildings (Pask, 1969). This is one of the architectural beliefs (Fisher, 2016) that represents architecture as a system or system-like, which is constituted of a set of interconnected structural components that have behavioural characteristics or processes generating outputs from inputs, and the parts are connected by distinctive structural and behavioural relations (Boyce, 1969). This belief reformulates the role of the architect to extend beyond the responsibility of designing the physical artefact of the building to its interactivity with the users. This school of thoughts raised the movement of Responsive Architecture (Celani, Sperling and Franco, 2015). This movement is motivated by data and data exchange is key in achieving such systems.

2.2.2. Early Digital Data Utilisation in Architecture

Negroponte (1970) - who is a pioneer of the infusion of computer processes in architecture – was interested in the relationship between the architect, the computer and the media of intelligence, instructions and feedback. His thoughts were revolutionary as he used the term “Architecture Machine” not to describe machines that “do” architecture, but machines that are capable of learning about architecture and even learning how to learn about architecture. For Negroponte (1969), architects and machines establish two-way intelligent dialogues and a partnership that can produce an evolutionary system. Negroponte’s theory predated the current data revolution and presented a machine that did not exist at that time. However, this machine is more likely with the current advancement of digital computing. The question of what is the nature of this machine and what is the role of the architect in relation to them is fundamental.

To summarise the above: Corbusier symbolised the traditional architectural process where the building is the machine and the architects are in charge. Libeskind designed a machine that allowed the public to create architecture and the architect is a facilitator. Pask expanded this to design an interactive system of inputs and outputs with users in mind (Haque, 2007), where architects program the system to interact with and adapt to users. Negroponte proposed an Artificial Intelligence process where the machine can create architecture on its own, and architects are teachers. These four views from Corbusier, Libeskind, Pask and Negroponte identify different methods where machine and architecture work together.

One further point regarding the nature of Negroponte's machine is that he defined five "sub-assemblies" that would be part of what he defines as an Architecture Machine: a heuristic mechanism, a rote apparatus, a conditioning device, a reward selector and a forgetting convenience (Negroponte, 1969). Each of these sub-assemblies reflects a component of a specific process as following: Heuristic mechanism refers to the process of searching and limiting the search results for a personalised solution (Search and Elect). Rote apparatus refers to the storing of an event or a trigger and associates it with a response when a situation is repeatedly encountered (Stimulus–Response Register). Conditioning device refers to the implementation component that saves and stores common information allowing natural responses of the machine (Data Management). Reward selector refers to the capability of the machine in identifying and registering the action and intervention that the teacher, "the architect", likes. Also, this refers to the option of allowing the architect to direct, simulate and override the machine (Stimulated Learning and Override). Forgetting convenience refers to a disremembered attribute that allows the machine to erase obsolete and incorrect knowledge. In addition to these sub-assemblies, the Architecture Machine, according to Negroponte (1969), would have a local computing power (Processor) and local memory (Data Storage) that enables it to work 24 hours a day. Negroponte's machine and descriptions match what today's digital data systems are supposed to have. Moreover, his thinking matches the belief of architecture as holistic design logic that is presented in the previous section. This thinking is a change in the architect's role in the design process from being a designer of the building to being a designer of the system that designs the building.

2.2.3. The Contribution of Recent Technologies to the Data Revolution

In this section, an overall understanding of current digital technologies is presented with the aim of discussing how developments in technology have changed the way data is used and understood in architecture. The discussion discloses that the current technological advancement implies an approach to a data-driven integrated design process.

Computer Aided Design (CAD) emerged in the early 1960s (Shah and Mäntylä, 1995) to replace the manual drafting process. CAD was adopted in architecture and has proven to be cost effective. At first, it was only capable of achieving two-dimensional drawings. By the mid 1960s it became capable of drawing three-dimensional ones (Myers, 1998). This highlights the beginning of digital technologies as a drafting tool. Four areas that have influenced CAD modelling were identified by Requicha (1980): Computer numerical control (CNC) machines, Sculptured Subdivision Modelling (SSM), Computer Graphics and Finite Element Method (FEM).

According to Grobman (2008), architecture 3-D models are developed by the following methods: polygonal meshes, solid models or parametric models such as Non-uniform rational basis spline (NURBS). Grobman (2008) explained that the tools architects use can be defined through the following categories: Drafting and modelling software; Parametric software programs for architects; Modelling software originally designed for other professions; Simulation and evaluation software; and Generation software. Gero (1995) identified different 3D computational processes in design including simulation, optimisation, generation, decomposition, constraint satisfaction, and search and exploration. According to this, the 3D digital technologies have offered different operations in the design process. Kalay (2004) identified five roles for computers in the design process: design tools, means of communication, design assistant, design environment and virtual environment. These roles were confirmed by a recent small survey of the tools used by practising architects in the US (Soebarto et al., 2015). These tools (Figure 8) reflect the workflows and operational methods of the practices involved in the survey. The survey indicated that architects rely on sketching and drawing as a primary design tool, followed by utilising three digital tools and technologies: Sketch Up, which represents a simple 3D modelling tool, AutoCAD, which represents a drafting tool, and Revit, which is a Building Information Modelling (BIM) tool. These tools have cross features, but the main driver is the architectural representation. The same survey showed the rise of Building Performance tools, which were categorised under "Other". Comparing this survey to the NBS 2017 survey (Figure 9) shows different results. In the NBS survey, it is clear that the use of Autodesk Revit which is a BIM-ready tool is dominant, while the use of Sketch

Up is limited. However, AutoCAD use has the same ranking in both surveys. These differences cannot be ignored. It is clear that no survey actually maps how architects use the digital tools universally. It all depends on the context and the surveyed sample.

Regardless the results, the previous discussion revealed that the development of technology has contributed to the expanding of data uses and types. Data utilisation in architectural design advanced from merely utilising geometric 2D and 3D data, to utilising 3D-information-embedded data (BIM), and finally to utilising occupants' behaviour and performance-based data. This advancement increased the amount of data in architectural design and operation, and correspondingly affected the design workflows and processes, which have been evolving to accommodate and acquire that increased amount of data.

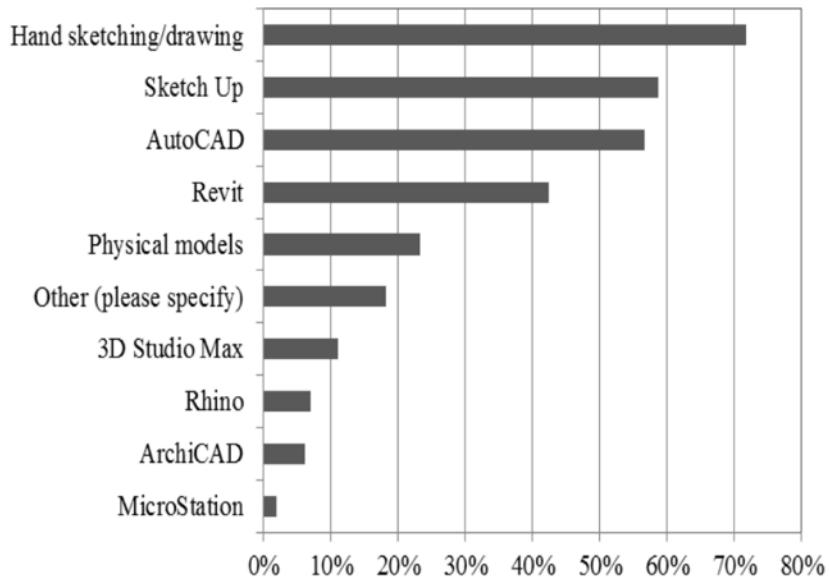


Figure 8 Design and Communication Tools in Architectural Practice (Soebarto et al., 2015)

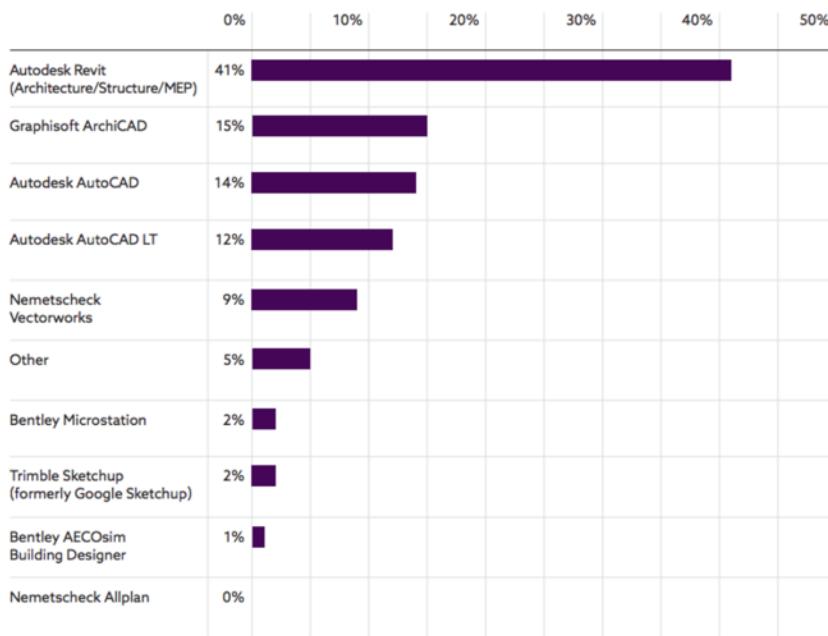


Figure 9 The Main Tools Used to Produce Drawings According to the National BIM Survey (NBS 2017)

The following figure (Figure 10) shows the impact of computers on the design process according to Grobman (2008). The figure confirms that the technological changes affected all design stages, leading to more access to information for the different project processes. The direct correlation of data, technology and design process is evident, and recently, with the revolution of data technology (*Big Data* and the *Internet of Things*) and data as a driver, an advancement of the design process is required. To address this change in the design process, an understanding of *Big Data* and the *Internet of Things* is necessary.

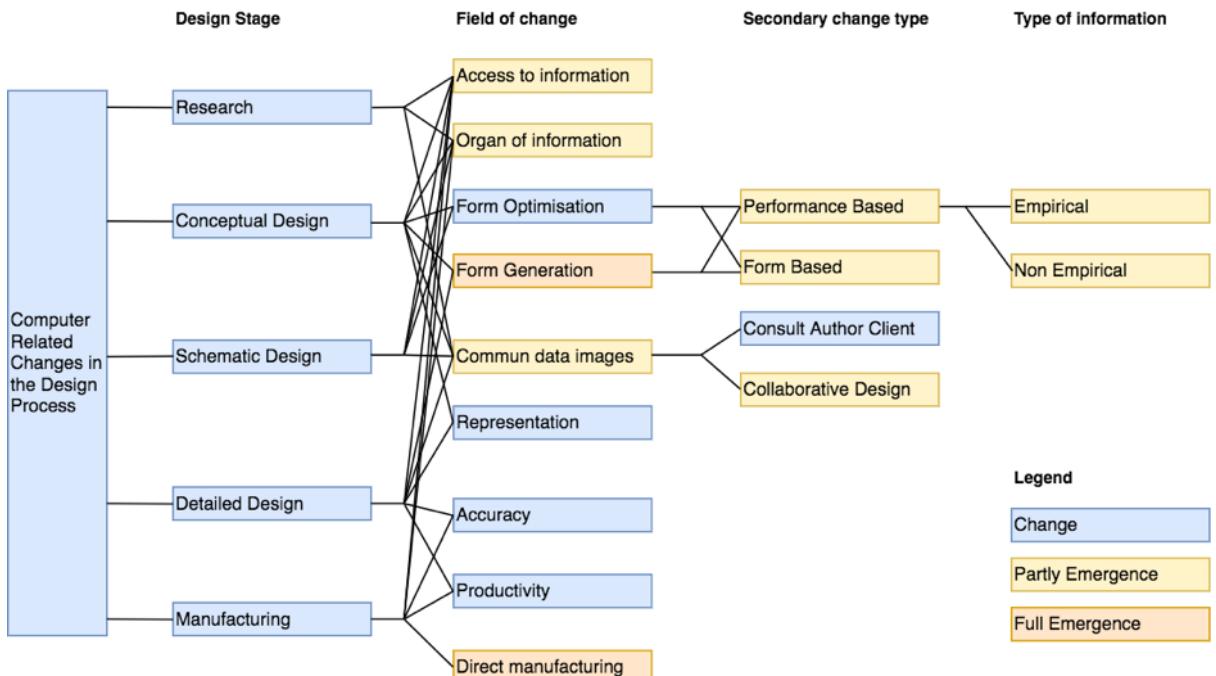


Figure 10 The Impact of Computers on The Design Process (Grobman, 2008)

2.3. Big Data and the Internet of Things

Big Data and the *Internet of Things* have had an impact on the various industries that preceded architecture. Investigating the data technology in other contexts provides an understanding of the possible impact of this technology on the design process and business in architecture. In this section of the chapter, an investigation of the definition of *Big Data* and the *Internet of Things* is achieved, followed by an examination of *Big Data* types and associated terms, and finally examples of *Big Data* are provided.

2.3.1. Definition

Data is not new to design and the built environment. In fact, architects and architecture businesses have always relied on data for decades. However, three factors determine what is considered new, and they are a consequence of the disruptive technologies including *Big Data* and the *Internet of Things*. The first is the vast amount of available digital data, the second is the low cost of acquiring and processing this data as it is available everywhere, and the third is the high value obtained from this process.

In a digital age where computing is ubiquitous and implemented in the built environment, and data is generated, monitored and harvested every moment, it is impossible not to think of data exchange and utilisation being a part of the design, construction and operation of architecture. The built environment has become a hub of data. An example of that is the use of Wi-Fi technology. Wi-Fi is part of every building in developing and developed countries nowadays; it is increasingly considered a necessity, as essential as other infrastructures such as water and electricity. Having a good internet connection is part of the benefits of daily living. However, such technology offers an infrastructure for the utilisation of other data applications.

The emergence of smart building technologies and the opportunity of providing better indoor services and greater control which is operated through mobile and handheld technologies is an example of the digital capability of data. However, the use of such technologies contributes to generating big amount of data that is hard to control and manage (Chen & Zhang, 2014). This phenomena of having big amount of data is referred to as *Big Data*. There is an ambiguity about the first use of the term *Big Data*. *Big Data* as a concept is not new. In fact, the first use of the term dates to the 1990s, when it was used by John Mashey, who was a chief scientist at Silicon Graphics (Lohr, 2013). What is new about *Big Data* is the actual applicability of the concept, and the availability of relevant technology to support it.

The McKinsey Global Institute report titled “*Big Data*: The next frontier for innovation, competition, and productivity” defined *Big Data* as “datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyse” (Manyika et al., 2011, p. 1). IBM defined *Big Data* with the four V's based on its characteristics: Volume, Velocity, Variety and Veracity (IBM *Big Data* and Analytics Hub, 2013). *Big Data* is a broad term that is associated with the multi-use of data and information. An example of *Big Data* in architecture is the significant amount of data generated or acquired through the design, the construction and the occupancy of the built environment, including data generated by designers, constructors, the building and post-occupant users. The whole process of planning, design, construction and occupancy is very complex. The process relies heavily on the exchange and communication of data. It operates using 2D and 3D data, and it

handles financial and corporate records, documents and schedules. In addition to that, the post-completion of the construction process keeps generating an enormous amount of data on the daily run. All this data cannot be managed without the right data tools (John Walker, 2014). Since having a big amount of data can lead to having a big amount of unstructured and unused information. And this is referred to as information explosion (Beath et al., 2012).

The concept of information explosion can be tracked to 1941 (Press, 2013). Information explosion refers to the rapid increment of the published amount of data and information. Historically, the data boom started in libraries and physical archives. At that time, it was due to the invention of the printing press. As the technology evolved, it became possible to carry information using digital devices instead of paper; data was employed in almost all new devices and played a significant role in the development and operation of their technology; this was accompanied by the extensive use of the internet, and digital datasets and resources became popular. New devices were generating a big amount of information, and the possibility of connecting these devices made it possible for the *Internet of Things* to exist. Data exists everywhere and in almost every object (Xia et al., 2012).

The *Internet of Things* technology is “the interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send and receive data” (SAS, 2015). The *Internet of Things* is the concept of providing everyday objects with built-in sensors that allow the gathering of various data which is connected and utilised for different applications across the network (Weber & Weber, 2010; Rose, 2014). An example of this technology is the sensors in buildings that automate and adjust heat and light according to specific triggers. A building with automatic functions is identified as a smart building (Kortuem et al, 2010). Smart buildings are operating on the use of data and the *Internet of Things*. Buildings are becoming hubs of sensors, smart meters and connected equipment. The first use of the term the *Internet of Things* was in 1999 by Kevin Ashton (Gubbi et al., 2013), which is the same year that the term *Big Data* was coined. This shows the historical correlation between *Big Data* and the *Internet of Things*.

Big Data and the *Internet of Things* are the collection of Digital Data, not only the data generated in sensors, but also the data generated using digital technologies in the design process. Since *Big Data* and the *Internet of Things* are defined, it is necessary to answer the question about what types of data exist in *Big Data* and the *Internet of Things*, in order to verify the existence of such data in architecture. *Big Data* and the *Internet of Things* types are not different from the types of data defined earlier, but rather present different categorisation for defining data based on the analysis process.

2.3.2. Categories

The challenge in utilising *Big Data* lies in extracting valuable information from all the different types of data available. In this part, an introduction of the various types of *Big Data* that are identified in the Information Technology domain is presented. These types are not limited to Information Technology but are also applicable in architecture and Construction. *Big Data* and the *Internet of Things* are categorised according to their structure, data processes and the type of data generated.

In relation the data structure, *Big Data* and the *Internet of Things* have three categories: Structured, Unstructured and Semi-Structured (Gandomi and Haider, 2015). According to the author, Structured data is any data that can be processed in a fixed format. An example of Structured data is data stored in tabular format. Unstructured data is any data that does not have a known format for processing it; an example of this is mixed data sources that contain text, images and video such as Google search results. Semi-Structured data contains both of Structure and Unstructured data. An example of Semi-Structured Data is the extensible mark-up language (XML)[°] file. This categorisation of data refers to the method of which data can be logged and can be queried. This categorisation is a good start for defining the process of analytics in the software. Structured data would be the easiest to deal with as the data would have standard format that is usually numerical or text-based. On the other hand, Unstructured data would be the most difficult to process because of the variation in format and the existence of non-text images which requires specific algorithms to verify. Unstructured data when divided can be

[°] See Appendix 2: Terminologies for the terminology

understood easier by human but can present a challenge for machines. Semi-Structured data is an intermediate categorisation that can be understood by machine and human together.

In relation to the data process, Kanellos (2016) defines five types of *Big Data* and the *Internet of Things*: *Big Data*, Fast Data, Dark Data, Lost Data and New Data. According to him, *Big Data* is defined as the information generated through a standard predictive analysis technique to achieve knowledge discovery and pattern recognition. Fast Data is information generated through rapid analysis of real-time data to provide quick and accurate answers to the current enquiry. Dark Data is information that is difficult to obtain and to use, such as video streams and photographs that are generated by security cameras. These data fall into the Unstructured data categorisation mentioned earlier. Also, some of the Dark Data is disclosed for security reasons. Lost Data is operational data generated by equipment and objects with no further use. New Data is information that is desired for future use but the technology and method of generating it does not currently exist (Kanellos, 2016). These categorisations of data provide clarification of the general use of the term *Big Data* and reflect the fundamental processes associated with it.

In relation to the generated data types, *Big Data* and the *Internet of Things* (IOT) have four types of data: Status Data, Location Data, Automation Data and Actionable Data (Friedman, 2015). For Friedman, Status Data is the basic type of IOT data, which is generated from almost all devices to show the status of the device. An example of this is the data generated from mobile phones to indicate that the device is on and connected to the network. Location Data is the data generated based on the Global Positioning System (GPS). An example of this type of data is Geotagging in construction equipment. Automation Data is data generated to automate a process or service. For instance, the data automating the smart thermostat in a house to save energy. Actionable Data is data generated to promote or stimulate an action without interfering with the system. An example that is similar to the previous one, rather than having the Automation Data adjusting the thermostat to a higher temperature, the system notifies the room occupier of the high use of electricity, and the occupier takes the action to set the thermostat higher or even turn off the system.

When assessing architectural data, these *Big Data* and *Internet of Things* types already exist in architecture. Starting to recognise and to sort data according to these types might be useful before applying the analysis. These data will be referred to later in Chapter 4 (Case Studies). This discussion has covered the different types of *Big Data* and the *Internet of Things* and provided an understanding of each. An example of such technology applications is given to support the discussion in the following subsection.

2.3.3. Applications Outside Architecture

Many cases demonstrate the benefits of adopting *Big Data* and *Internet of Things* technologies outside the architectural business domain. Most of these businesses are service-based. In the following paragraphs, some examples from different sectors are given.

The healthcare sector is considered one of those that benefit the most from this technology (Manyika et al., 2013). One of these applications is the utilisation of personal wearable technology such as a wrist-wearable health tracker to promote a healthier lifestyle. Companies such as Nike, Fitbit and Basis have developed these products, which operate alongside an online personal dashboard. The products allow users to adopt small and progressive health changes over time (Diaz et al., 2015). This utilised data is Actionable Data which is very specific to the gadget user.

Another sector is transportation and specifically airlines. British Airways has developed a loyalty programme, "Know me", which allows certain data to be collected from their customers based on their online behaviour; this data is then combined with their loyalty programme information to deliver customised offers. The programme permits their services to be evaluated passively to provide a better and more positive experience for their customers (Tckhakaia et al., 2015). Another example is Delta Airlines, which provides a data-based service that allows their customers to track their bags and luggage from mobile devices, providing an easier travelling experience (Wyld et al., 2005). In both examples the information is generated based on datasets and Automation Data.

Also, media and production sectors have benefited from data collection and

analytics to provide better TV shows and programmes. For example, Netflix collects data about the international viewing habits of millions of their customers, which allows them to buy and create programmes with more assurance that they will be accepted and embraced by their viewers (Gomez-Uribe & Hunt, 2016). Netflix uses a combination of Location Data and Automation Data to achieve their recommendation programme.

These are samples of *Big Data* and *Internet of Things* applications. Simple and effective measures are taken based on processing vast amounts of data, which brings benefits to both businesses and users.

2.4. Big Data and the Internet of Things in the Architecture Business

This section expands the discussion of the business side of *Big Data* and *Internet of Things*, focusing on the existing business models in utilising these technologies. The section covers *Big Data* and *Internet of Things* models and connects them to disruptive models in architecture. The aim of this connection is to establish the concept of data-driven operation as an approach in architecture. Finally, the section investigates a framework of Data-Driven business models to identify data operations that provide components that are necessary for the case studies analysis.

Before getting into describing and discussing *Big Data* and the *Internet of Things* Business Models, a definition of what Business Models denote in this research is necessary. Business models have many definitions. Zott, Amit and Mass (2011) presented a comprehensive literature review covering many of these definitions. To prevent any ambiguity in this thesis, a specific definition has been determined in which business model refers to the specific activities and operations employed by a business to achieve a certain business objective. In the context of *Big Data* and the *Internet of Things*, a business model signifies the digital data activities that rely on the existence of the technology of *Big Data* and the *Internet of Things* to achieve a business objective.

2.4.1. Big Data and Internet of Things Business Models

Big Data and the *Internet of Things* technologies are creating new markets, operations and values for various sectors. New business models have emerged, including Data-Driven business models, and have been adopted in industries such as health and transportation. Data-driven business models include: Software as a Service (SaaS), Platform as a Service (PaaS) and Data as a Service (DaaS).

In a report published by the McKinsey Global Institute (Henke et al., 2016), these data and analytics business models were referred to as disruptive models. Disruptive in business is a term used to refer to an innovation that creates a new market and value that eventually disrupts the existing market (Markides, 2006). In the same report (Henke et al., 2016), six archetypes of disruption models were identified in various domains, as shown in Figure 11. The listed domains have “Smart cities and infrastructure” under “Hyper-scale, real-time matching” and “Enhanced decision making”. Also, “Material sciences” are listed under “Data-driven discovery”. These domains are linked directly to architecture. These domains are highlighted in the figure. Figure 11 confirms the current impact of *Big Data* and the *Internet of Things* in proposing new business models in architecture. Three archetypes are obtained from the figure: Hyper-scale, real-time matching, Data-driven discovery and Enhanced decision making.

Identifying the business models without investigating the operations implicated in them is not methodically sufficient. Thus, in the following section, an investigation of Data-Driven business models and the components associated with the data operation is presented. These components are utilised in analysing the case studies (Chapter 4), of which the analysis contributes to building the Data-Driven Operational Framework for architecture.

Archetype of disruption	Domains that could be disrupted
Business models enabled by orthogonal data	<ul style="list-style-type: none"> ▪ Insurance ▪ Health care ▪ Human capital/talent
Hyperscale, real-time matching	<ul style="list-style-type: none"> ▪ Transportation and logistics ▪ Automotive ▪ Smart cities and infrastructure
Radical personalization	<ul style="list-style-type: none"> ▪ Health care ▪ Retail ▪ Media ▪ Education
Massive data integration capabilities	<ul style="list-style-type: none"> ▪ Banking ▪ Insurance ▪ Public sector ▪ Human capital/talent
Data-driven discovery	<ul style="list-style-type: none"> ▪ Life sciences and pharmaceuticals ▪ Material sciences ▪ Technology
Enhanced decision making	<ul style="list-style-type: none"> ▪ Smart cities ▪ Health care ▪ Insurance ▪ Human capital/talent

Figure 11 Data and Analytics Six Disruptive Models (Henke Et Al., 2016)

2.4.2. Data-Driven Business Models (DDBM)

Investigating existing Data-Driven Operational models permits an understanding of how these models operate outside the AEC domain. This understanding provides the knowledge foundation for the process, models and involved business components, of which the concepts and methods can be derived or transformed and repurposed for the AEC industry. The focus is on the operational side of data, as the aim is to build a Data-Driven Operational Mode for architecture.

Research by Brownlow et al. (2015) argues that creating a data-driven business model requires the business to answer six primary questions:

- What does it want to achieve by using data?
- What is the desired data offering?
- What data is required and how it is acquired?
- By what methods is data processed and applied?
- How is data monetised?
- What are the barriers to accomplishing the goal?

Although these questions are not based on the architectural sector, the first four

questions are relevant to this research as they are addressing the data operations. These questions aim to frame what is required in building a data-driven business model. The first question refers to the intention of using data such as achieve a better architectural design. The second question indicates the format which is needed to achieve the intention such as numerical measurements for design spaces. The third question refers to the source for data inquiry and how to acquire the data. An example of this is the source being a database for best architectural designs around the world. The fourth question refers to the method of processing data such as comparative analysis based on human satisfaction of the design. To summarise the framework according to Brownlow et al. (2015) have Intention, Desired Format, Data Sources and Data Methods. This model can be useful in employing data-driven methods for obtaining a specific answer for a defined question with a pre-known format. It would not be efficient to apply such a model for discovering new patterns or inquiring unknown data sources.

Zolnowski et al. (2016) identified the effects of data-driven innovations on business models based on Partner, Company and Customer Perspective. For the author, the data-driven innovations affect the following categories: Finance (Cost Structure), Infrastructure (Key Resources and Key Activities), Value (Value Proposition), and Interface (Relationship and Channel). Finance (Revenue Stream). This categorisation proposes improved components for data-driven business models as the model is not based on answering a question but instead focuses on the process of data-driven.

One integrated Data-Driven Business Model framework was proposed by Hartmann et al., (2014). This structure was derived from researching a sample of 100 business start-ups which utilised data-driven business models. The companies were selected from five sectors: Finance, Insurance, Publishing, Retail and Telecoms. The collected data about the sampled companies was coded according to the available literature of data-driven business models. The output was a generalised Data-Driven Business Model framework that has the main constituents and operations associated with this approach. The DDBM framework by Hartmann et al. (2014) has six established components: Data Sources, Key Activity, Offering, Target Customer, Revenue Model, Specific Cost Advantage. Figure 12 shows this

Data-Driven Business Model. In this model, Data sources refer to the source of input data, whether it is external or internal. Key activities relate to the data processes used such as acquisition and analysis. Offering refers to the output of data activities and the value that the data is creating, for instance, information and services. These three components (Data Sources, Key Activity and Offering) are common among the previously mentioned frameworks. And these comprise the data operation and can be used to identify the data process. Thus, these components are utilised in the analysis of the architectural data operations, which Chapter 4 (Case Studies) covers. However, the other components such as Target Customer and Revenue Model exist outside the scope of this thesis.

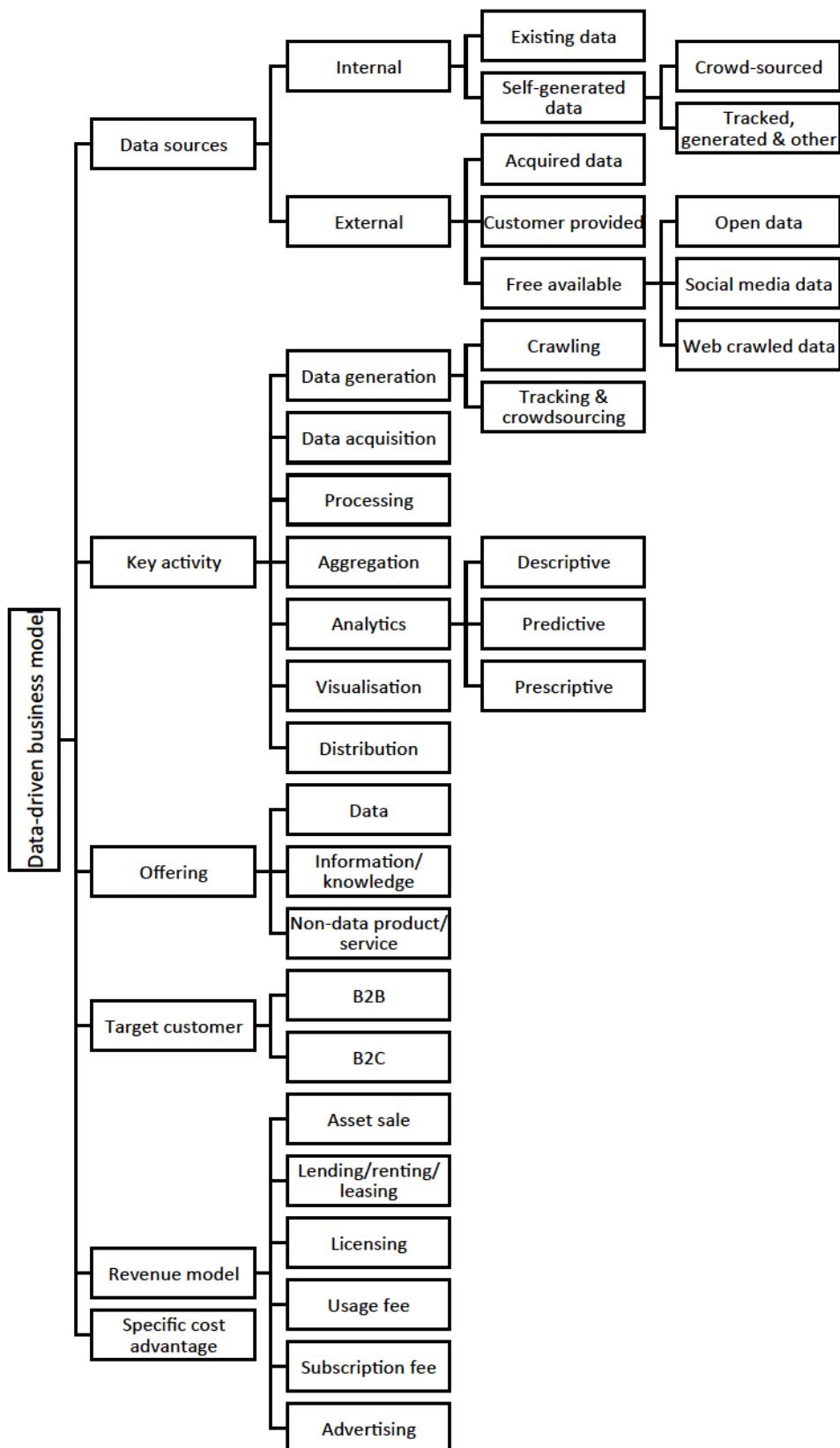


Figure 12 The Data-Driven Business-Model Framework (Hartmann et al., 2014)

2.4.3. Challenges and Opportunities in Addressing Data-Driven Techniques in Architecture

In architecture, so much emphasis is placed on the design and the creation aspects of the profession rather than on the business and profit aspects. Architects feel uncomfortable talking about money. Gerber and Lemermeyer (2012) argue that architectural schools teach upcoming architects how to design buildings, but they do not prepare them to run a business. This argument indicates a deficiency in the education of architects regarding the financial side of their businesses (Fairs, 2018). And this deficiency contributes to the lack of clear identification of business models and design operations in the sector (Smith, 2016). Employing innovative business models in architecture is one way for architects to adapt to the changes in the industry and environment (Brown, 2009). The increase in the economic success of the business will give an architect a better chance to have a greater impact on the society and the built environment.

Defining and adopting a data-driven architecture operational models has the potential to enhance the running and the sustainability of the business from many aspects including financial, environmental and impact. The reason is that architects know how to deal with data. But they require a basic understanding how to employ it as a business model. RIBA (2014) has identified four general approaches for architects, urban designers and planners when working with data. These approaches are: meeting users' needs; experimentation and modelling; analysing data to improve local and national policy making and implementation; and improving transparency to speed up development processes. These approaches are proposed as a refinement to what architects already do rather than changing or reformulating the way they operate. The data-driven operational models that this thesis proposes could contribute to giving architects innovative business approaches with the use of *Big Data* and the *Internet of Things*, in addition to allowing them to utilise useful data from other sectors and industries, as data collected in one industry can be utilised, for unrelated purposes, in an entirely different domain (Henke et al., 2016).

However, there are many challenges facing architects when working with data. One of the challenges is due to the additional time and efforts involved in utilising data-

driven operations as part of the design process (Sailer, Pomeroy and Haslem, 2015; Deutsch, 2015). This data utilisation requires extra training, resources and time, which are not guaranteed to benefit the architects. Adopting data-driven operations creates a risk that most architects prefer to avoid. Another challenge relates to the changes in the culture: the changes in the process affect the current culture of architectural design and operation (Deutsch, 2015). And operating data-driven techniques need a change in the architects' education and required skills (Nicol & Pilling, 2005). These changes demand more collaboration and integration between architects and stakeholders at an early stage of the project (Whyte, 2015). Collaboration is another challenge in the design process due to the involvement of various stakeholders. Each stakeholder requires certain type of data and there is a need to effectively address, manage and integrate data between them timely (Mahdavi et al., 2014). The last challenge that faces architects when working with data is presented by the design contracts and liability issues (Miller, 2012). This challenges how architects' service contracts are written and who is responsible for the utilised and generated data, especially in an industry that has various stakeholders.

Data is seen as too abstracted and yet restricting in the design process; however, the right utilisation of data-driven operational models might allow architects to enhance their design outcomes with data while keeping the creative side of their practice.

2.5. Summary

In this chapter, *Big Data* and the *Internet of Things* have been investigated from an architectural perspective. An investigation of data in architectural design as Ideology, Profession and Service led to value being highlighted as the main operator when using data, and the anticipated value is crucial in deciding how data could be employed. This outcome led to further investigation of value, which the following chapter (Chapter 3: Value in Architecture) covers.

The chapter also discussed the digital change in the architectural workflows and how this change has contributed to the current data revolution. Moreover, the chapter introduced *Big Data* and the *Internet of Things* technologies in relation to their application, associated business models and architectural relevance. Finally, the

data-driven operational model was proposed as an innovative approach to responding to the current changes in the profession. Three components of data-driven operational models were identified to be used in the Case Studies chapter (Chapter 4).

Chapter 3: Value in Architecture Design

'A designer has his own standards. He is a professional, a craftsman, and if he is good himself, he knows when he has done a good job. It must be all of a piece, have wholeness, clarity, it must not be too strong at one point and not too weak at another, but, as I said, it is useless to try to define quality. All we can say is that its emergence results from the involvement of the designer, from his passion for perfection, from the fever which grips him when he sees the chance of producing a really good job, and which makes him sustain the effort involved'. (Arup, 1972 cited in Emmitt, Prins and den Otter, 2009, p. 3)

The chapter focuses on the investigation of value, which is briefly presented in the previous chapter in the investigation of data in architectural design as Ideology, Profession and Service. The chapter aims to identify value, and what value means to architectural design and architectural operation in particular, to understand how value is implemented through the use of data, in addition to examining value creation in the architectural design process and operation in the built environment. The aim of this investigation is to provide an answer to what values architecture and architects bring to the built environment.

The main objective of this chapter is to establish an understanding of the Digital Value as part of the existing values in the built environment. Through this chapter, a value taxonomy in architecture is established with the aim of achieving three purposes: the first purpose is allowing the Digital Value to emerge as part of the existing value systems. The third purpose is to provide an understanding of the impact of values on the operation processes by investigating how value is applied in Design.

In order to achieve the specified objectives a mapping of existing values is essential to understand value; this is followed by investigating valuation methods in architecture and the built environment through a comparative analysis. This investigation relates values to architectural data and styles. Finally, the concept of Digital Value is proposed.

It is important to mention that the properties and definition of the term values vary according to domain, practice and business. In this thesis, the focus is the value of the architectural design and the operations associated with the business of architecture.

3.1. Value and Value Creation

Diving into investigating data processes in the built environment without understanding what data can bring to the field does not allow a comprehensive understanding of the process and the potential it provides. As established in the previous chapter, value dictates data.

There have been many efforts through history to define and evaluate value such as the views of Pirsig, Thomas Van Acquino and Smith (Emmitt et al., 2009). Many philosophical views and debates have emerged through time and going through each definition is not this research's concern. However, it is necessary to highlight some of the most notable definitions to support the background knowledge.

Value as a general term in dictionary means worth or price. The concept of value is defined as the relationship between benefits received and costs incurred (Jupp et al. 2010). This means that value refers to the expenses between what is given and what is taken. Value is defined as "The balance of benefits and sacrifices involved in a judgement of worth; hence positive and negative value; creation and destruction of value. In most derived definitions, the word 'Value' is deemed to be preceded by the adjective positive" (Saxon, 2005, p. 10). In this definition, the value is deemed as a criterion to provide judgement; this judgement is relevant to the process in which it is employed. According to this, values in the plural are defined as "Criteria for judging value, subjective to the judge and based on culture, role in the transaction and personal experience" (Saxon, 2005, p. 10). Saxon definition of values relates value judgment to three aspects, individual experience, the role between giving or taking and the surrounding culture. This definition does not clearly explain what experience means, does it refer to the individual past experience or his ability to think and take decisions or even a combination of both. Pirsig (1999) in his theory about the 'metaphysics of quality' defined value as 'pure' experience proceeding rational thinking. This definition refers to value as the

experience obtained from rational thinking. The experience gained from rational thinking matches what knowledge is (Zagzebski, 1999). Thus, it is possible to declare that good knowledge means good value. For Pirsig, ‘value’ is undefinable and complex to judge in terms of quality with relation to object and subject. This view is seen in the dualism between quantitative (classical) and qualitative (romantic) appraisal systems. Pirsig’s definition is an attempt to cross the division between science and art, between data and value. However, Pirsig’s search for quality ends at a philosophical level (Volker, 2010). In dictionary, architecture is defined as the art and science of designing buildings. This combination of science and art (Moore, 1965) allows architecture to be appraised according to both classical and romantic appraisal systems. It is essential to define the nature of this value before getting into the different types of architectural values and value creation.

3.2. Architectural Value Between “Extrinsic” and “Intrinsic”

The Value Theory has been used in various approaches in philosophy (Schroeder, 2008). Value theory is often referred to as “Axiology”, which is the classification of ethics and aesthetic values. The Value Theory provides methods to understand how people value things. Utilising the concepts and approaches of the Value Theory provides a perspective on understanding values in architecture. In this section, a discussion of the value theory is presented to understand how the value in architecture is perceived.

The theory of value in economics is concerned with the exchange value of goods and services. From an economic perspective, architecture can be considered both a good, as in the final product, which is the building and the built environment, and a service, as in the design and procurement process.

According to Schroeder (2008), The theory of value divides value into two main types: Intrinsic (objective) value and extrinsic (subjective) value. These categories differentiate how values are assessed. The Intrinsic value is concerned with the value that the object, good or service holds. A simple example of this is that a chair made of marble is more valuable than a chair made of wood because marble is more expensive than wood. Extrinsic value is an external or subjective assessment of

something's worth in relation to certain factors and regardless of its intrinsic properties. A simple example of this is that: for a Modern architect, a Modern chair made of wood is more valuable than a Victorian chair made of gold. The Extrinsic value is always external and usually set by the individual under the influence of many factors. These influences could be meeting requirements, wishes, desires or fulfilling a sustainable environmental footprint. Extrinsic value is valid in architecture only if the actual building exists and can be experienced. However, the Extrinsic value does not explain how values are implemented through the design process.

Hartman (2011) added another type of value, "Systematic" to the existing ones. In his theory, "Formal Axiology", he categorises value into three types: Intrinsic, Extrinsic and Systematic. According to Hartman, Systematic values are the original concepts and ideas of how things should be. Systematic values are not internal or external; they are conceptual and exist only in the mind of the assessor. The Systematic value comprises systematic and precise criteria of definitions or ideals including goals, structured thinking, laws, policies, procedures and rules (Hartman, 1967). Systematic values are collective constructive values of how things should be. This type of value is the one that architects bring to and control in the design process. The architectural design process can be realised as sets of concepts and instruments to achieve a Systematic value (Holm, 2006). An example of this: a building is not a building if it does not have a roof and walls. Nevertheless, the more complex the definition, the more complex the assessment will be. Valuating a green building requires a precise definition of what a green building is and in this context. Hartman (1967) summarises that there are three kinds of concepts to be fulfilled by each value: construct (Systematic), abstract (Extrinsic) and singular (Intrinsic).

Getting back to questioning where architecture and architectural design values are positioned, a proposal which follows the previous knowledge of 'Formal Axiology' is implied. Architecture design and knowledge have the following hierarchy: Architect, Design and Building. The architect takes a decision under the influence of the client requirements which becomes the design and eventually the building. The architect is singular, the design process has Systematic properties, and, finally, the building has Extrinsic ones (Figure 13). This distinction of properties in the

hierarchy of design allows each one to be assessed as a type of value in itself. The architect can be assessed as an Intrinsic value, the design as a Systematic value and the building as an Extrinsic value. This rationalisation clarifies the definition and the relationships of values in architecture. According to this, all values start as Intrinsic, are adopted as Systematic and, finally, are presented as Extrinsic.

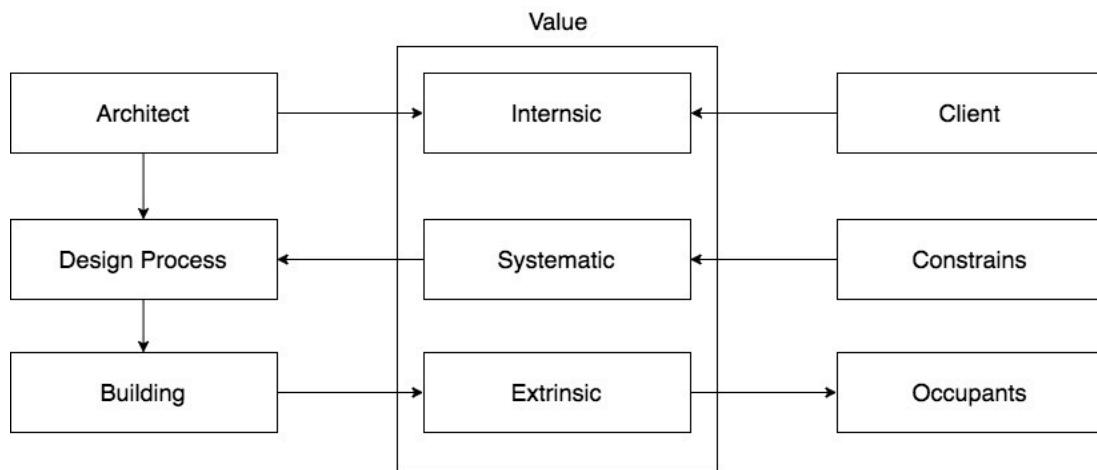


Figure 13 Value Employed in Architecture Design

From the previous discussion, the value implemented in the design process is of a Systematic type and can only be defined by sets of rules or concepts of how the building should be. However, this Systematic value that the architects control is influenced by many other factors, and these factors include the architect's intuition, available data and the client's brief. In the following section, a discussion of the Systematic Value from different perspectives and the factors that contribute to it is presented.

The 'value theory' provides a method which allows the establishment of a taxonomy of values in architecture. The "value theory" is addressed in the following section.

3.3. Architecture Value Between Architects, Clients and Occupants

In order to determine how the stakeholders as a factor affect the Systematic value that exists in the architectural design, a review of values from the perspective of selected stakeholders including the architect is presented.

3.3.1. Examples of Values in Architecture from the Architect's Perspective

The seeking of value and value creation has been part of the architectural practice since the beginning of the profession (MacMillan, 2004). The value terminologies used are diverse: value did and still refers to using other terms such as qualities, properties and rationale. But in essence they all reflect the systematic values that the architect chooses to achieve.

Value in architecture is implemented in the process of design in history. One of the essential established principles for architectural value comes from Vitruvius's "Ten Books on Architecture". Vitruvius defines three types of values: 'Utilitas' (function, commodity, utility), 'Firmitas' (solidity, materiality, sustainability) and 'Venustas' (beauty, delight, desire). What Vitruvius has created is a type of Systematic Value that allows the design to be assessed according to this criterion. However, Vitruvius did not elaborate upon these terms, which led to people redefining their own meaning over time (Johnston, 1997). An example of this is the modern use of these three principles in the Design Quality Indicator method (discussed further in this chapter). John Ruskin in his book "The Seven Lamps of Architecture" described seven values that architecture of quality must include. The seven lamps are Sacrifice, Truth, Power, Beauty, Life, Memory and Obedience (Ruskin, 2009). These values set the characteristics of the Gothic Revival. Although these values are relevant to the time in which they were employed, some of the principles are still applicable today. It is possible to observe that Ruskin's values are very specific and have more humanistic characteristics that are implied metaphorically. An example of this is the value Memory. The factors that make buildings memorable and monumental is subjective and dependable on the time of observation. Some buildings become memorable simply because of age. A building might not be memorable in the year of built, but years later it becomes memorable for another generation of human civilisation. However, Vitruvius values are more generalised and can be observed in buildings at most times.

Architecture has acquired various value systems through the development of different movements in history. These movements allowed classical and contemporary managerial ideas to be employed in architecture. Some of these movements competed to define what value means. An example is the radical shifts

in design values emerged in the development of Modern and Post-modern architectural design movements (Larson, 1995). These movements reflect values that originated within the design history and indicate the current technological and social state of architecture and design (Holm, 2006). For example, Art Nouveau was the first attempt to replace the classical system of values in architecture. The classical system was seen as decorative, and decorations were not considered of value anymore (Colquhoun, 2002). Art Nouveau faced the problem of saving historical values while introducing new ones. Starting from Art Nouveau, Modern architecture elevates function and originates the form based on it. Modern architecture is based on the principles of form follows function, staying true to materials, and achieving a purity of form (Lidwell, Holden and Butler, 2010). Also, there is an emphasis on redefining aesthetics which is connected to the famous statement “Less is More” by the modern architect Ludwig Mies van der Rohe.

The previously mentioned systems of design principles are Systematic Values that reflect the architectural style of that time. This Systematic value is the core of architectural styles and movements which reflect the technology and conditions of the time in which they emerge. Architects today still utilise values employed in these architectural styles, and sometimes refer to these styles themselves in their design decisions. It is difficult to say there is one right approach for implementing values in architecture, but the architect’s Intrinsic values direct the Systematic values employed in design.

Other value definitions have emerged in literature and practice in contemporary architecture. Alexander (2004) indicates that value is the “wholeness”, which is a characteristic of all natural and well-designed beauty. He identifies 15 fundamental natural properties of wholeness, as follows: Levels of scale, Strong centres, Thick boundaries, Alternating repetition, Positive space, Good shape, Local symmetries, Deep interlock and ambiguity, Contrast, Gradients, Roughness, Echoes, The void, Simplicity and inner calm, and, finally, Not-separateness. Alexander’s properties set criteria and rules to achieve the value of beauty. However, such properties have geometric aspects and allow other values to emerge. What Alexander has created is a Systematic Value. For him, the Systematic Value is manifested in language patterns that provide descriptions of the qualities of spaces of various scales (house,

neighbourhood and town), which architects have addressed through time. The language patterns are intended to support the design process. Alexander's work shows that the Systematic Value could be language-based.

Ove Arup in his work aimed to achieve what he called excellence in design as an approach to the achievement of value. He differentiated between two types of value in the design and construction process: measurable value and immeasurable value (Emmitt, Prins and den Otter, 2009). The measurable value represents the commodity as defined by the design brief, while the immeasurable value represents the extra commodity, the delight or artistic quality and the social price. Arup defines excellence in design with the formula shown in Figure 14. Arup's Systematic Value is based on a formula he created; using this formula he projected different factors contributing to this value. These factors for Arup are: the design brief defined by the client, the added service, the delight and artistic quality which is defined by the designer, the price (Exchange) and finally the social aspect. Notice that Arup includes price as a factor in achieving excellence. This reflects the economic changes in the practice at his time.

$$E = (C + EC + D) / (P + SP)$$

(E) is efficiency or excellence in design, (C) is commodity as defined by the design brief, (EC) is the excess commodity of that is defined, (D) is delight or artistic quality, (P) is price, (SP) is the Social Price (Emmitt, Prins & den Otter, 2009). Arup answer for the immeasurable value is consulting advisors to decide why and what to build. Also, this formula can explain the concept of value and added value.

Figure 14 Arup's Value Formula (Emmitt, Prins and den Otter, 2009, p. 3)

It is negligent to deny the success of which Ove Arup has achieved in the construction industry as a well-known businessman, and regardless the accuracy of this formula and the reality that it worked for his business and contributed to achieving value, it is no accurate to put a universal formula for attaining value in the built environment. Most of the mentioned variables in this formula are not necessary quantifiable, and the context of each built project is different. What is considered valuable for the designers, the clients, the occupants in one project is not necessarily valuable for other projects.

In the previous discussion, it is realised that in contemporary design, the Systematic values are more descriptive and can be more clearly defined. Moreover, the architect's contribution to addressing value is clearly represented, and his or her skill set became key for this contribution. Understanding the contemporary architects' skill sets leads to understanding the values they bring to the design process. In recent research concerning the value of architecture in homes and neighbourhoods, a small sample of literature materials from industries, charity and academic reports were reviewed to detect the type of work associated with architects. Four types of architecture skill sets were identified: Commercial, Cultural, Technological and Social (Samuel, 2014). Figure 15 shows these types. The same figure refers to Academic Architecture as another type and shows that there is a minor overlap between the different identified types. This reference to academia highlights that education plays a big role in equipping architects with a comprehensive knowledge with regard to the various Systematic Value types, which leads them to expand their work in a specific type of Systematic Value after graduation. In these types of architects and the suggested values, there is an emergent and an emphasis on the Commercial and the Academic values which reflects the rise of commercial and academic sectors in practice. Samuel's values are more universal and previous sets of values such as Vitruvius's can be mapped across the suggested classification.

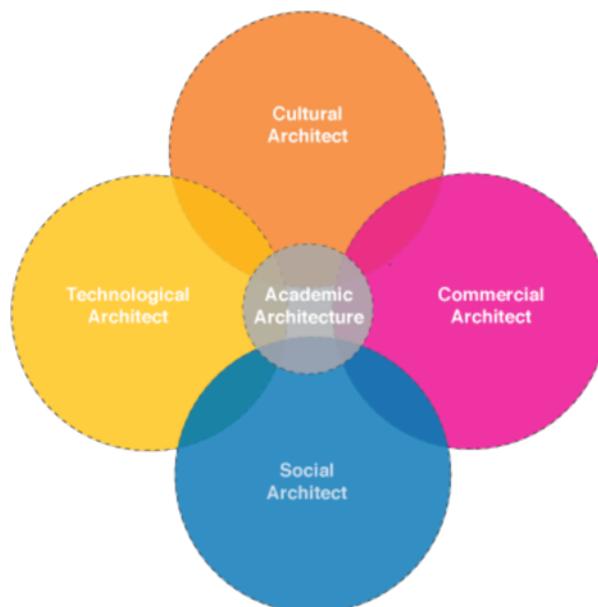


Figure 15 Types of Architects (Samuel, 2014)

These types (Social, Technological, Cultural and Commercial) are influencing factors of the Systematic value within which architects operate. Dividing the value system according to the architect's skills could be one way to understand the bigger picture of their contribution. This division of values reflects the cultural change of the architect's role from being a grand designer who controls every aspect of the design into a specialist with specified contributions to the design.

3.3.2. Values in Architecture from the Stakeholders' Perspective

Occupiers are the last stakeholders of the architecture in the architecture design cycle. The value that they gain from the architecture design is represented by how the design is contributing to meeting their needs (Koskela, 2000). A design that satisfies more needs has a higher value. In order to understand the occupiers' basic needs, which leads to understanding the value from their perspective, Maslow's hierarchy of human needs (Figure 16) is utilised. The pyramid divides human needs into three bands: Self-fulfilment, Psychological needs and Basic needs.

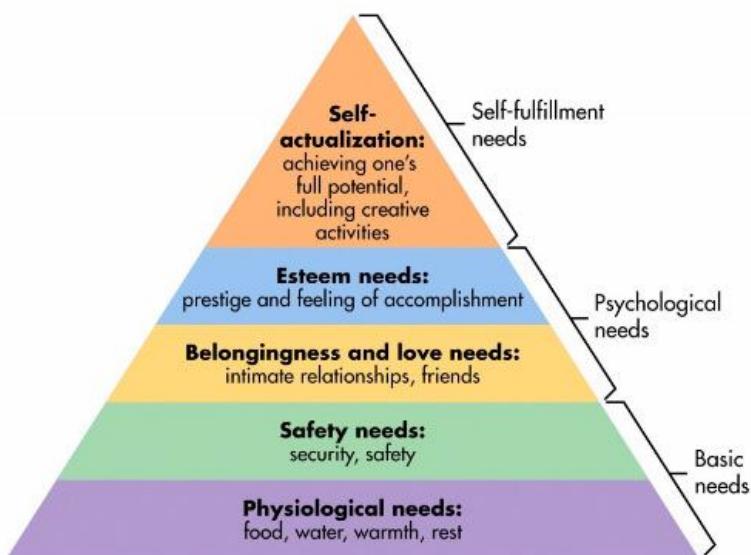


Figure 16 Maslow's Hierarchy of Human Needs (Mcleod, 2007)

This pyramid provides a foundation for value understanding based on the fact that built environments are made to serve human needs (Doumato, 1981). The architectural space should allow these human requirements to be addressed and met. A transformation of this pyramid into design values that match the existing

hierarchy is achieved based on mapping each need to its correspondence value. Each level has been transformed into different types of values as the following: Self-fulfilment and needs are represented in Image and Culture; Psychological needs are represented in Social and Environment; Basic needs are represented in Functionality and Usability. The whole pyramid represents a Systematic Value for how architecture design is supposed to meet occupiers and users' needs. A spatial attributes pyramid is presented (Figure 17).

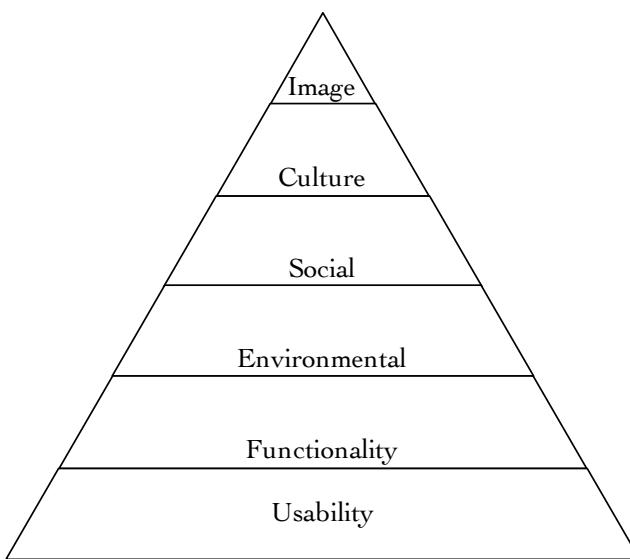


Figure 17 The Spatial Attributes Pyramid (Adapted from McLeod 2007)

The previous reviews of values in the built environment show that values are complex and have many facets. What is deemed as of value for one stakeholder could be a disadvantage for another, and this can cause a conflict in the design process and delivery. In architectural design, the building is the final product that is designed by architects with the aim of addressing the needs of clients and users.

The building is constructed by contractors and has an impact on the environment and the life of the public when built. The Systematic Value is derived from one member of the design cycle to another with the aim of providing more benefits. Values in architectural design are supposed to address a broad range of requirements, and this is one of the reasons why value has different types, such as cultural, ethical, aesthetical, philosophical and social, which are expressed in the public and professional domains. In addition to these mentioned types, there are

other types such as organisational, functional, technical and economic aspects, which are influenced by clients, users and the other stakeholders.

In the previous section, the Systematic Value that contemporary architects employ in architectural design is discussed by identifying the different types of architects. This value does not solely depend on architects as all stakeholders are identified as a factor that affects this value. A discussion about the values from the perspective of the occupiers as one of these stakeholders was discussed. However, not all the involved stakeholders were considered. Investigating the other involved stakeholders would provide a clearer understanding of the Systematic Value.

It is difficult to identify all the stakeholders who are involved in the architectural design project (Tzortzopoulos et al., 2006). However, it is possible to investigate some of the researches that aimed to do so. For example, MacMillan (2004) identified the following categories of stakeholders: Finance, Design and Construction, Occupant and Organisation, Public Realm and Visitors. combining the work of MacMillan (2004) and Tzortzopoulos et al, (2008) provides clearer understanding of clients' taxonomies and their activities in the built environment. Table 3 shows the stakeholders, their categories and expected outcomes. The expected outcome clarifies what type of values these stakeholders have on the design process. Also, A new column (Codes) was added to describe the type of expected outcome by each of them.

Table 3 Stakeholders and Value Outcomes

Category	Client Type	Stakeholders	Outcomes	Codes
Finance (a)	Paying Clients (c)	<ul style="list-style-type: none"> • Financiers • Banks • PFI consortia • Developers (f) • Government 	<ul style="list-style-type: none"> • Return on capital profitability (a) • Long-term value (a) • Ease of letting or selling awards (a) 	Capital
Design and Construction (a)	Experience in Construction (b)	<ul style="list-style-type: none"> • Architects • Engineers • Surveyors • Designers • Consultants 	<ul style="list-style-type: none"> • Profitability (a) • Repeat business (a) • Awards (a) • Prestige (a) 	Capital

		<ul style="list-style-type: none"> • Contractors • Sub-contractors • Suppliers 		
Occupant and Organisation (a)	End Users (d)	<ul style="list-style-type: none"> • Chief Executive, • Project Directors, Communications and Marketing Managers • General Workforce • Human Resources • Facilities Managers • Security Staff • Cleaners • User's Representatives • Users 	<ul style="list-style-type: none"> • Organisational productivity and profitability (a) • Organisational vision, image and identity (a) • Corporate brand and reputation (a) • Corporate social responsibility, good working environment (a) • Staff health and well-being (a) • Recruitment and retention, absenteeism (a) • Energy and maintenance costs (a) 	Capital Image Psychology Health and well-being
Visitors to building (a)	End Users (d)	<ul style="list-style-type: none"> • Hospital patients • Hotel guests • Retail customers • Students, pupils • The public 	<ul style="list-style-type: none"> • Hospital recovery rates (a) • Comfort levels • Retail footfall (a) • Educational achievements (a) 	Health and Well-being Psychology
Public Realm (a)	User Representatives (e)	<ul style="list-style-type: none"> • Local authority • Local community • Regional and national community 	<ul style="list-style-type: none"> • Regeneration and inward investment (a) • Impact on property values, pollution, local health (a) • Empowering end users. • Employment, civic pride, neighbourly behaviour, vandalism (a) 	Capital Health and Safety Environment

Sources:

- a) (MacMillan, 2004)
- b) (Tzortzopoulos et al., 2008)
- c) (Zeisel, 1984)
- d) (Edmondson, 1992)
- e) (Boyd and Chinyio, 2006)
- f) (Masterman and Gameson, 1994)

From the previous table (Table 3), the following expected values for the involved stakeholders in the design process can be identified: Capital, Image, Health and Well-being, Safety, Environment and Performance. Although certain values that are desired by stakeholders could be identified, it is not clear what are the measures of such values.

One problem associated with creating, obtaining and assessing values in the built environment is the measurement of these values. A good design is expected to bring the maximum values possible for the stakeholders and the environment (RIBA, 2011). However, the values of good designs are not always tangible; they are often intangible. Economic exchange values such as capital and cost-benefit can be measured in numbers and currency, but exchange value solely does not define a good design. Focusing on the exchange value and implementing a cost-driven approach in the design might impact the design negatively. Most values in the built environment are hard to measure in traditional ways (Ewing and Handy, 2009), making it hard to validate them in the building or even through the design process. However, a study of these intangible values might reveal the measures and indicators associated with them.

A study of the valuation of these intangible values in the built environment was carried out by MacMillan (2004) through a structured workshop. An initial mapping for categories was created. Other researches including the work of MacMillan (2006), Volker (2010), McIntyre (2006) identified the types of these values and the indicators associated with them. Table 4 represents these types. The outcomes of these studies indicate the need for a matrix approach to assisting values in the built environment.

Table 4 Types of Values and Value Indicators in the Built Environment

Type of value created	Bundle of valued outcomes
Exchange value (a,e)	Building as a commodity to be traded: commercial value is measured by the price that the market is willing to pay. For the owner, this is the book value, for the developer the return on capital and profitability. It also covers issues such as ease of letting and disposability.
Use value (a,e)	Contribution of the building to organisational outcomes: productivity, profitability, competitiveness and repeat business, and arises from a working environment that is safe in use, that promotes staff health, well-being and job satisfaction, that encourages flexible working, teamwork and communication, and enhances recruitment and retention while reducing absenteeism. Measures will vary sector by sector but might include recovery rates, footfall, examination results, and occupant satisfaction
Image value (a,e)	Contribution of the building to corporate identity, prestige, vision and reputation, demonstrating commitment to design excellence or to innovation, to openness, or as part of a brand image.
Social value (a, d)	Buildings that make connections between people, creating or enhancing opportunities for positive social interaction, reinforcing social identity and civic pride, encouraging social inclusion and contributing towards improved social health, prosperity, morale, goodwill, neighbourly behaviour, safety and security, while reducing vandalism and crime
Environmental value (a, d, g)	The added value arising from a concern for intergenerational equity, the protection of biodiversity and the precautionary principle in relation to consumption of finite resources. The principles include adaptability and/or flexibility, robustness and low maintenance, and the application of a whole life cost approach, and the immediate benefits are to local health and pollution.
Cultural value (a,f)	A measure of a building's contribution to the urban fabric. Cultural value may include consideration of highly intangible issues like symbolism, inspiration and aesthetics. Indicators of cultural value may include critical press opinion.
Sources:	
a) MacMillan (2004)	d) McIntyre (2006)
b) MacMillan (2006)	e) Loe, E. (2000)
c) Volker (2010)	f) Holden, J. (2004)
	g) The Design Council Cabe. (2006)

These values are considered in analysing the case studies in Chapter 4. The values extracted are: Exchange, Use, Image, Social, Environmental and Cultural. These values are used in assessing the value brought by the Operational Models in the case studies. In order to assess the case studies based on these values, a valuation method should be implied. In the following section, existing Valuation methods in the built environment are presented and discussed. A comparison between them is established to understand how certain values emerge.

3.4. Valuation methods in the Business of the Built Environment

Various valuation methods are adopted in the built environment to support or to evaluate design and building decisions. The Design Council Cabe (2006) has published a major report The Value Handbook addressing the value subject; some of its findings were discussed in the previous sections. The Value Handbook provides an evaluation sheet which aims to help architects in assessing the design quality of their buildings (MacMillan, 2004). This type of evaluation is qualitative as it is based on the architect's self-assessment and reflection. The Value Handbook also provides resources to help translate this assessment into actions. After mapping different valuation methods in the built environment, a conclusion was made that there are two types, quantitative and qualitative. In this section, a summary of the investigated valuation methods is presented overlooking the value's type. The reason for this is to highlight the valuation process rather than the type of values they promote. The main aim of investigating these valuation methods is to understand how they are incorporated into the design process. Also, the investigation aims to recognise what types of value systems they implement, and whether digital technologies have the potential to support and address the shortcomings in these methods.

Before presenting the valuation methods, it is necessary to address the fact that the concept of implementing value into the design process is not new. One of the first attempts to implement value as part of the business process was proposed by Lawrence Miles during his time at General Electric company. Miles used the term "Value Engineering". The Value Engineering methodology was adopted for the first time during World War II (Miles, 2015). The Value Engineering concept focuses on the value in the relationship of function to cost.

Some of the valuation methods from the design perspective that exist in the built environment and which are investigated here are the following, in order: Hedonics, Design Quality Indicators, VALiD, Contingent Valuation Method and Contingent Choice Modelling and DART.

3.4.1. Hedonic

This valuation method emerged from Ecological Economics. The Hedonic valuation method focuses on the exchange value of the built environment. It has been used widely in real states (Monson, 2009). This method estimates the economic value of the built environment based on its environmental characteristics and the provided services. These features are associated with either the environment qualities or the environmental amenities. The valuation method considers these characteristics and their demands and relates the exchange value to these characteristics. A change in the exchange value of the built environment reflects the significance of these characteristics. This method is based on data collection for amenity values. Although the hedonic method focuses on the exchange value, it has been used to assist the experience of the occupant as a driver for the architectural design (Loftcheva, 2014). However, this is a unique adaptation and is not considered a replacement for the actual method.

An example of applying the Hedonic method in architectural design is basing design decisions on what people consider valuable regarding location and facility. The value is defined by individuals and assessed by architects.

The main valuation formula of the hedonic method is the following: $\text{Market Price} = f \text{ where } f \text{ is the coefficient generated from the regression analysis with regard to the tangible and building characteristics, in addition to other influencing factors.}$

What is good about the Hedonics valuation method is the potential of capturing the economic impact of environmental elements on the built environment as part of the design. However, since this method is based on market demands and prices, it ignores any building that is out of that market (Mulgan, 2006).

3.4.2. Design Quality Indicator

The Design Quality Indicator is a valuation method that assists the building's stakeholders in defining and investigating the design quality at key stages in the design and development process. The Design Quality Indicator (DQI) requires the involvement of an assigned facilitator in the process. The facilitator is required to be independent and accredited.

The DQI has three parts: The Questionnaire Part, the Weightings Part, and the Reporting Part. The questionnaire aims to capture views from all stakeholders based on a structured assessment of Vitruvius's three principles: Functionality (Utilities), Build Quality (Firmitas) and Impact (Venustas). Figure 18 shows these the integration of these principles. The Weightings Part aims to gather the perception of stakeholders regarding various aspects of the building, analyse these views and divide these aspects into three categories: Fundamental, Added Value and Excellence. The Reporting Part produces reports that provide a detailed analysis of the findings, visualisations for comparisons and recommendations for further improvements.

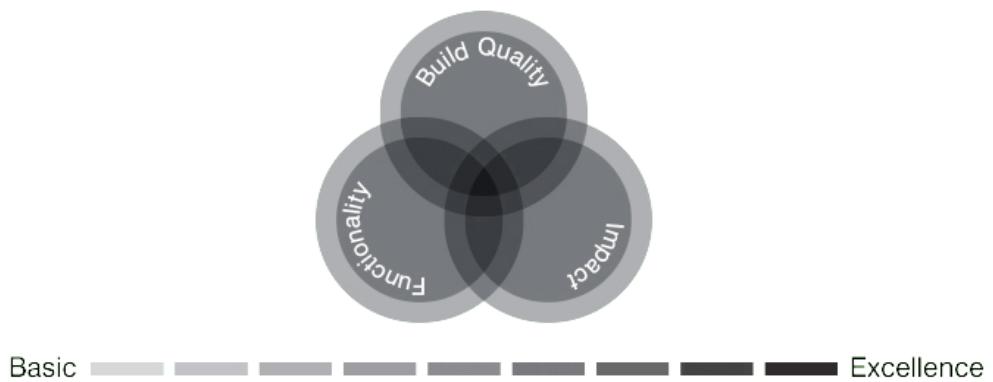


Figure 18 Vitruvius's Principles in The DQI (DQI, 2013)

Each one of these principles has a specific definition. Functionality is concerned with the building's design, and it is composed of use, access and space. Build Quality pertains to the structure's performance, and it is split into performance, engineering and construction. Impact refers to the building's positive effects on the community and the environment, and it is constituted of character and innovation, form and materials, internal environment, and urban and social integration. The following diagram (Figure 19) clarifies these qualities and their categorisations (Saxon, 2005).

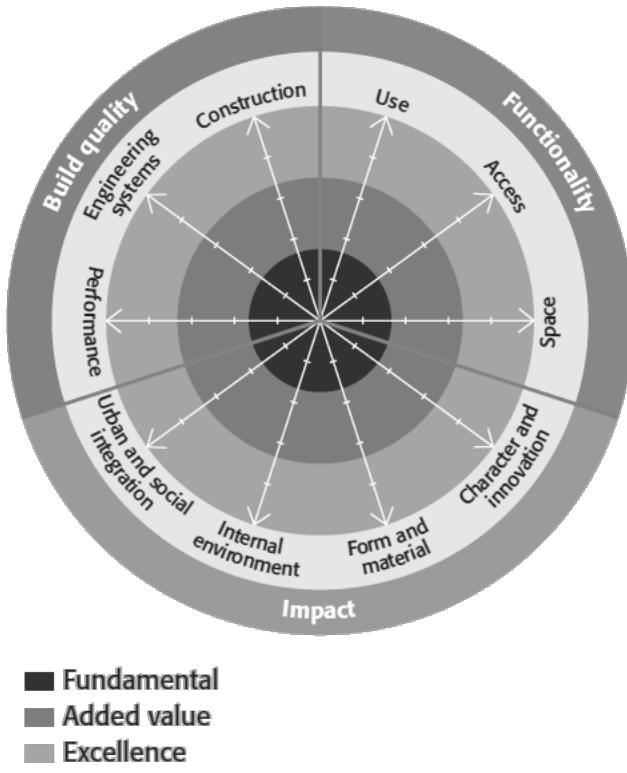


Figure 19 DQI Values and Categorisations (Saxon, 2005)

The DQI has an online web-based tool that can be accessed instantly or remotely. This method can be used during various stages of the design development, which include: strategic briefing stage, design briefing stage, mid-design and in-use ("How does DQI work?", 2013).

What is good about the DQI method is the possibility of involving many stakeholders in the valuation process and the availability of the web tool. However, a shortage in this method is that it focuses on the physical building as an element with less attention to public spaces (Mulgan, 2006). In addition, it requires a facilitator who is knowledgeable in the use of the method.

3.4.3. VALiD (Value in Design)

VALiD is a valuation method that is similar to DQI in the approach of integrating stakeholders' value judgements into the design development process through the VALiD framework. This framework presents a sequence of activities that are aligned with related stages of the design development process: Preparation, Design, Construction and Use. This method utilises people's judgements to understand stakeholder values and to demonstrate project performance.

The VALiD evaluation process has three stages, respectively: Understand Values, Define Values and Assessing Value. The Understanding Values stage aims to understand the value from each stakeholder's perspective and put together shared project values. The Defining Value stage seeks to establish a value proposition as a representative of each stakeholder is charged with expressing the value criteria and targets of its group and reflect these values against the project objectives. The Assessing Value stage aims to merge solutions, to translate them into action and to focus on value delivery.

Values are defined according to this method in using the following formula:

$$\text{Value} = \text{Benefits} - \text{Sacrifices/Resources}$$

This valuation method requires a facilitator similar to DQI. And it offers various instruments and techniques such as a structured value survey and a dashboard. VALiD depends mainly on the ability of the stakeholder's representative and his or her knowledge to express the organisation's values (VALiD, 2005).

The VALiD method permits the involvement of many stakeholders, this is considered an advantage of using this method. And unlike the DQI method, it has broader use that allows the integration of public spaces. and provides detailed results that includes compromising and costs (Mulgan, 2006). However, this method requires a facilitator who is expert about the implementation of the method and it requires the stakeholders to be clear about their desired values from the beginning of the valuation process.

3.4.4. Contingent Valuation Method (CVM)

The CVM is a valuation method that is used to measure exchange values in the built environment. It is adopted to measure the use and non-use (passive) values. It is a questionnaire-based method that directly involves people's responses in establishing economic values. People are asked to respond in currency terms. This approach is the opposite of observing their behaviours and actual needs. CVM is widely utilised in evaluating passive values as the questions are usually based on hypothetical

scenarios and situations. This valuation method is considered controversial, and its results are typically less useful (Ecosystem Valuation, 1999).

What is different and good about the CVM is the possibility of valuating passive and intangible values. However, it is unreliable as it is based on probability and possible scenarios (Mulgan, 2006).

3.4.5. Contingent Choice Modelling

This Valuation Method is similar to the Contingent Valuation Method and is based on the same approach. The only difference is that the established values are not represented in currency but rather concluded from hypothetical choices. The questionnaire allows the surveyed people to choose between different hypothetical scenarios. This valuation method is commonly used in determining policy options (Ecosystem Valuation, 1999).

The Contingent Choice Modelling allows the evaluation of passive value similar to the CVM. Since the method is based on the use of hypothetical choices, it is useful for determining policies (Mulgan, 2006). However, this method is unreliable as well, as it is based on probable scenarios.

3.4.6. The DART

The Dart is an interactive tool powered by United States-based Architectural Practice RTKL (The DART, 2016). The tool aims to guide designers to achieve a Performance-Driven Design. According to the RTKL website, the Performance-Driven Design improves the built environment. The tool has three steps: Identifying Variables, Strategy Selection and Prioritising the Strategies.

The first step aims to identify the important project values for the clients and community. The values are divided into three categories: Economic, Environmental and Social. A wheel of variables is used to enable clear value identification. The wheel is presented in Figure 20.



Figure 20 Variables Wheel in The DART Tool (The DART, 2016))

The Strategy Selection depends on the selected values. DART identifies a set of strategies that are developed to assess a particular value. Each strategy has a Value Impact rating which shows its potential and is followed by case studies as examples. The available strategies include: Connection to Outdoor, Daylighting, Efficient Envelopes, Material Health, Material Recovery, Material Use, Natural Ventilation, Plug Loads, Project's Potential Analysis, Renewable Energy, Right-Sizing, Site Planning, Site Selection, Solar Orientation and Control, Space Planning, System Use, and Water Management (The DART, 2016). The mentioned strategies are then prioritised based on their relevancy to the project phase and schedule to optimise the value acquisition. The priority levels from lower to higher are Project Suitability, Project Site, Building Shape, Building Material and Building Systems (The DART, 2016).

The DART method allows architects and designers to include clients or community in the design solutions based on the identified values and strategies. The DART

method is useful for involving different stakeholders in the valuation methods. Also, the well-defined values and strategies make it easy to use; this is in addition to the availability of the web tool. However, the definition of these values and strategies proposes a limitation to its use. Also, the method focuses on the valuation of a building and does not include the public spaces.

3.4.7. Analysis and Findings

A Qualitative comparative analysis of these different methods is achieved according to the following properties: Values Included, Method, Criteria, Values Outcome, Advantages, Disadvantages. The main aim of investigating these valuation methods is to understand how they are incorporated into the design process. Also, the investigation aims to recognise what types of value systems they implement, and whether digital technologies have the potential to support and address the shortcomings in these methods. Table 5 provides a comparison between these valuation methods based on Type, Values Included, Method, Criteria, Values Outcome, Advantages and Disadvantages.

Table 5 Valuation Methods in the Built Environment.

Valuation Method	Type	Values Included	Method	Criteria	Values Outcome	Advantages	Disadvantages
Hedonics	Quantitative	Environmental quality. Environmental amenities	-Survey-based	Demand	Exchange value	Captures economic contribution that environmental elements make to a development's private value.	-Ignores buildings for which there is no market. -Focuses on market demands
Design Quality Indicators	Qualitative	Functionality Build Quality Impact	-Questionnaire -Weightings -Reporting	Based on the defined values	Action-based solutions	- Involvement of different stakeholders - Has an online web tool	-No integration of public spaces -Requires facilitator -Stakeholders must be clear about their values
VALiD	Qualitative	Values are defined by stakeholders	-Understand values -Define values -Value assessment	Based on the defined values	Action-based solutions	-Involvement of different stakeholders - Detailed results -Includes compromising and cost	-Requires facilitator -Stakeholders must be clear about their values
Contingent Valuation Method	Quantitative	Future scenarios Possible policies	-Questionnaire based on hypothetical scenarios	Consumer preferences	Numeric exchange value	-Evaluating passive values	-Not reliable as it is based on probable scenarios
Contingent Choice Modelling	Qualitative	Defined attributes	-Questionnaire based on hypothetical scenarios	Consumer preferences	People's choice	-Evaluating passive values -Useful in determining policies.	-Not reliable as it is based on probable scenarios

DART	Qualitative	Economic Social Environmental	-Identifying variables -Strategies selection -Prioritising the strategies	Based on the selected values	Action-based strategies	-Defined values -Defined strategies -Has a webtool	-Limited to the defined values and strategies. -does not give attention to public spaces.
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From this analysis of the evaluation methods, it is possible to identify that the addressing of value takes place twice in the valuation process: at the beginning of the valuation process as an input of relevant data, and at the end as an outcome of information or solutions. The outcome value is rather an action-based strategy or a numeric value which gives information. In order to achieve the outcome value, each valuation method has a comprehensive stage of data collection, communication, analysing and transforming.

In addition to this, it is possible to identify that these valuation methods differ in the following: the stage of implementation, the valuation outcome, the valuation scenario and the involvement of stakeholders. The valuation methods are implemented and addressed according to the different stages of the design. Some valuation methods are utilised prior to the design, and others are utilised during and post the design. The quantitative valuation methods aim to deliver an Exchange Value, while the qualitative valuation methods provide strategies for other intangible values. Some of these valuation methods, such as Hedonics, aim to evaluate existing environmental conditions and scenarios, while others, such as the Contingent Valuation Method, simulate hypothetical scenarios to project a predicted value. Finally, some of these valuation methods, such as Design Quality Indicators and VALiD, allow the collaboration of different stakeholders. Hedonics does not include other stakeholders in the valuation process. Contingent Valuation Method and Contingent Choice Modelling aim to include people's preferences in the evaluation.

One of the main findings when analysing these valuation methods is the lack of full integration for how data is collected, analysed and transformed within the valuation and design process. Most of these values are predefined in the design process, and

there is an attempt to measure them along the process. However, there is no continuous assessment of what value has achieved in the process and the effect of such value on building or occupants.

Two issues were identified in evaluating these valuation methods: the first is that they are designed mainly for management purposes: the values are highlighted in the valuation process but separated from the design development and the final building. The second is that these methods are currently imposed on the design process and are not intended as part of the design operation itself. The valuation methods are realised externally, and the values did not emerge and realised internally through the process and the involved stakeholders. These issues arise due to the lack of sufficient data and feedback route across the whole project process, and this will change by using digital technologies and strategies such as *Big Data* and the *Internet of Things* techniques as part of the valuation method. Figure 21 shows this isolation between the valuation process and the design.

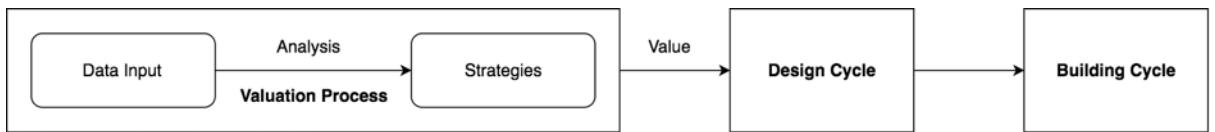


Figure 21 Existing Valuation Methods in Design and Build

3.5. Digital Data, Value and Architect

In Chapter 2, data was identified as the main component in any valuation method that seeks to add more value to the architectural design process. Building on the connection between value and data, and the understanding of digital data in Chapter 2, It is found necessary to add a new type of value. This added value is the Digital Value. The Digital Value allows other values to be generated and acquired. It is an extrinsic value as employing it would affect the generation of other values within the built environment, and it would influence the Systematic Value of the overall building. Figure 22 shows the proposed Digital Valuation method based on the literature review so far.

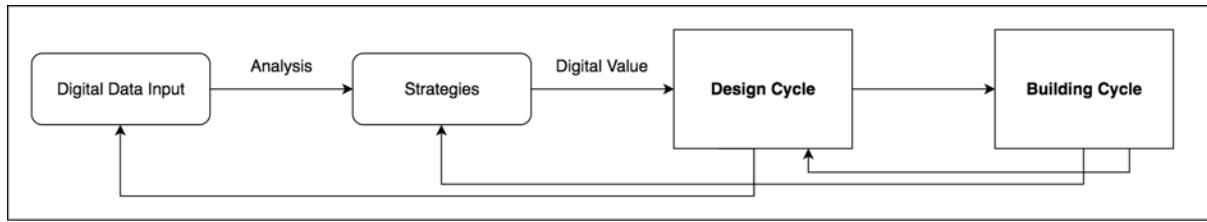


Figure 22 Proposed Digital Valuation Method

The Digital Value defines a new specialism for architects, a specialism that requires specific digital skills and knowledge to operate. Based on the types of Systematic Values identified earlier, A new type of architects is added, the Digital Architect, which take the roles of implementing the Digital value and designing a digital system that ensures that the Digital Value returns the other types of values in the design process. Figure 23 shows the addition and the position of the Digital Architect between the other types.

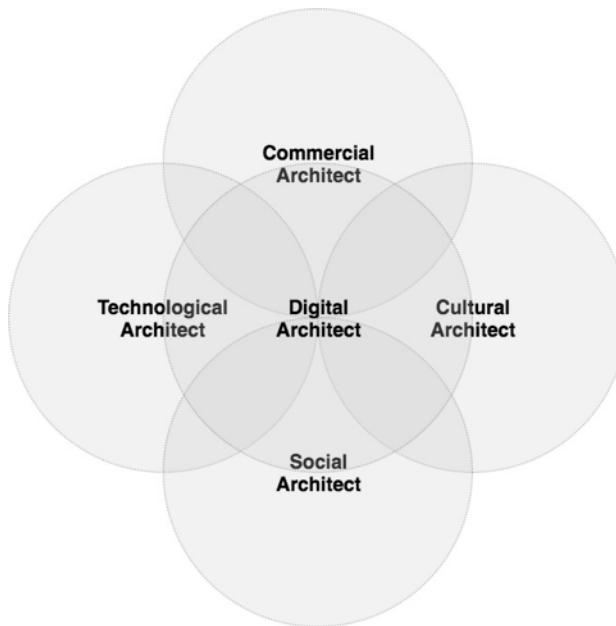


Figure 23 The Position of The Digital Architect (adapted from Samuel, 2014)

3.6. Digital Value Equaliser

To understand how digital value in the built environment enables other types of value to emerge, the concept of the Digital Value Equaliser is employed. This concept forms a method for the assessment of the digital value. This method aims to understand how the digital operation in the case studies enables other types of value to emerge. The equaliser is merely a conceptualisation and representation tool used

to show intangible values that are enabled through the use of the digital process. The Digital Value Equaliser offers flexibility as values are added according to the value coding of the case study and can be adjusted according to the value impact. Some of the architectural values depend on and affect other values and this will affect how the equaliser is presented. This conceptualisation of digital value is adopted in analysing each case study in Chapter 4 (Case Studies). Each case study will have a Digital Value Equaliser representing the values coded in the case presented along with a table of value coding. The alignment of the value bar to the right side of the reference line indicates the higher impact of this value in the case. The Digital Value Equaliser is useful to determine how the digital value contribute to the emerge of other types of values. Figure 24 shows the equaliser in a neutral representation. Figure 25 shows an example of the Digital Value Equaliser of case study 1.

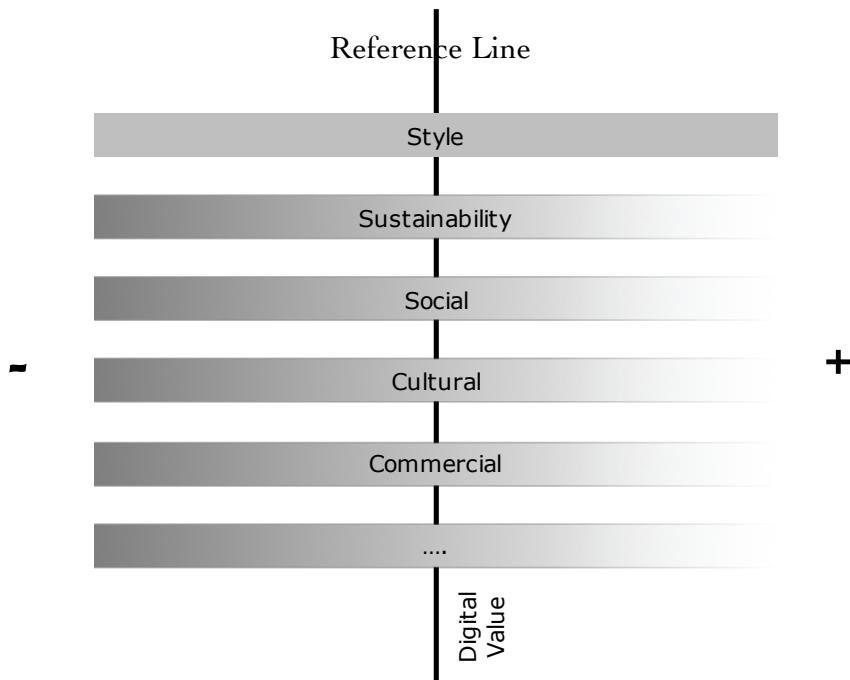


Figure 24 Neutral Representation of The Digital Value Equaliser

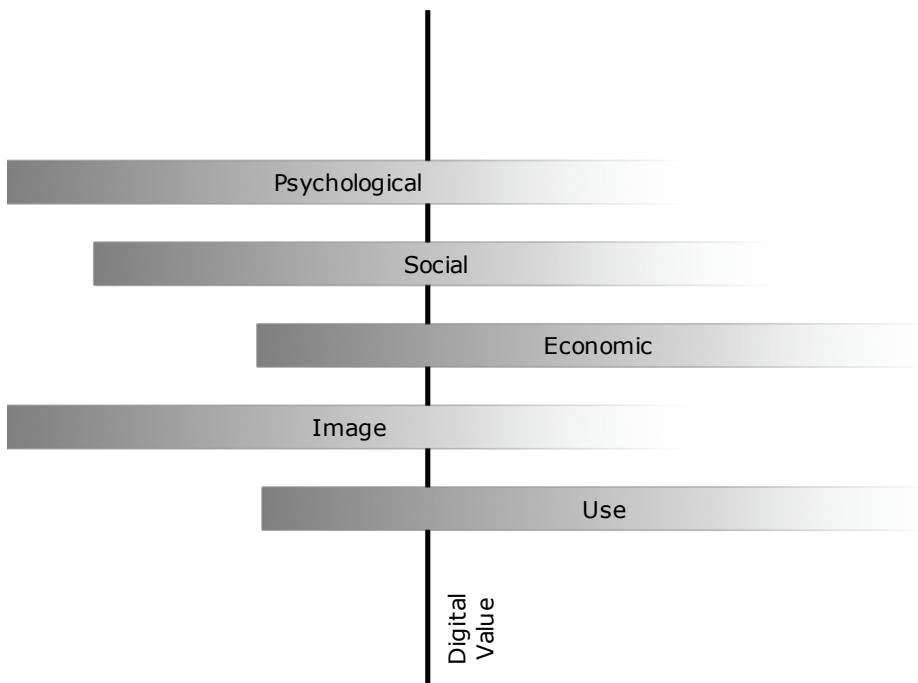


Figure 25 Case Study 1 Digital Value Equaliser

3.7. Summarising Data and Value

Values in the built environment are Intrinsic for architects, Extrinsic for buildings and Systematic for the design process. The Intrinsic value is based on the architect's knowledge, combined with cultural and social factors. This knowledge is facts, information and skills acquired through his/her architectural experience and education. Architectural information originates from data that is rooted in the profession, the culture and the society. Architects have acknowledged and transferred this data for generations. Realising the created values can enable the recreation of the same data for acquiring more values in future situations and scenarios.

It is arguable that architecture as a profession is based on the contemplation of data. When Vitruvius came up with his virtues in his famous book "De Architectura", he combined the knowledge, views and expertise of many architects and artists including Greeks and Romans. The same process is applied whenever a value system in architecture is established. Understanding that data creates value is critical. And that is the reason for redefining the Digital Value.

To make the connection between data and value again, the DIKW pyramid of data, information, knowledge and wisdom, which shows the hierarchy of these entries is used. The collection and organisation of data provide information, and the analysis, synthesis and interpretation of information provide knowledge (Jagdev, Brennan and Browne, 2004). Value can only be established on profound knowledge. Figure 26 shows the proposed Data-Knowledge-Value model.

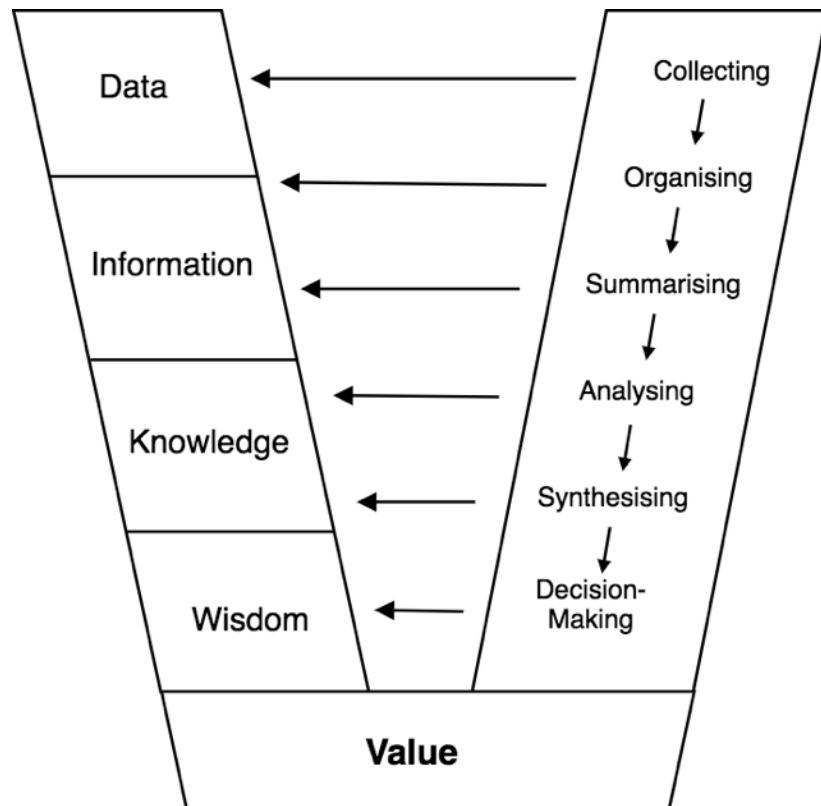


Figure 26 Data-Knowledge-Value model

The top-down approach of processing data provides deeper meaning and leads to value creation as presented in the DIKW pyramid in Figure 26. On the other hand, a bottom-up approach of applying a value allows types of data to be observed. Thinking of this pyramid from the architect's perspective clarifies how value is designated from data. Designing with a data-driven approach eases the decision-making process and addresses a higher level of needs for end-users. The only method that is enabling value to emerge from data is if data is consciously operated and used to drive the whole design process and business. The digital value equalisers concept, along with the discussed value systems, is utilised in the following chapter (Chapter 4) to analyse the case studies.

Chapter 4: Case Studies

This chapter provides information about the chosen case studies and informs the process of extracting knowledge with regard to data operations. Practical and academic cases that use data in the built environment are examined and analysed. This chapter discusses the case studies according to specific categorisation that emerged from the Open Coding of the Grounded Theory. This chapter discusses the case studies with the aim of achieving the following:

- Provide a deeper understanding of the data-driven operational process in architectural contexts
- Establish concepts and schemes of data-driven approaches in architecture
- Provide the required knowledge to build the Data-Driven Operational Framework which is explained in the following chapter (Chapter 5: The Development of the Data-Driven Operational Framework)

4.1. The Cases Selection

Case studies are effective to connect the theory with the practice. The descriptive and qualitative comparative analysis of different cases allows the identification of common variables. Each case provides a domain to investigate *Big Data* and the *Internet of Things* phenomena in the architectural design context. Each case is unique and specifically selected, but they all have similarities in the data implementation process. These similarities give *Theoretical Replication*[°]. The replication of the data implementation process enables the development of the framework (Yin, 2013). This method is adopted to develop the Data-Driven Operational Framework.

The research data is collected by reviewing the available literature on all cases. However, Participant Observation was carried out as part of reviewing and analysing the first case (Liverpool ONE Project). Participant Observation is a qualitative methodology that involves the researcher in the practice of certain method to gain close knowledge based on observation and involvement (DeWalt and DeWalt, 2010). In this case, the method is the implementation of data in design. This case provides a closer observation. The overall collected data is analysed

[°] See Appendix 2: Terminologies for terminology

through the Grounded Theory coding categories focusing on the processes of implementing data.

Regarding the definition and the wide domain of *Big Data* and the *Internet of Things*, it is practically impossible to find one single case that is optimum, and which covers the whole features of the technology, as there are many implementations of *Big Data* and the *Internet of Things* in various industries. However, it was necessary to consider several cases where data was utilised in a defined architectural scope. Having a definite scope makes each case analytically manageable. Consequently, the analysis provides more accurate results. The domain of these cases is not entirely and purely architecture due to two reasons: first, architecture influences many other aspects of humanity such as cultural, environmental and social. Thus, it is possible to include other applications in the process. Second, *Big Data* and the *Internet of Things* are still emergent phenomena that depend on Information and Communication Technologies (ICT).

The case studies seek to provide the necessary knowledge to:

- Identify the main components of the data-driven operational models and framework.
- Sub-categorise the data-driven model components and define them from an architectural perspective.
- Identify the relationship between the various architectural data-driven framework components.
- Identify the relative processes and data-handling methods.

The case selection process continued over a certain period. Cases were added and removed frequently until data reached saturation, and the analysis had eight main case studies. Whenever a new case was added, a comparative analysis was carried out to identify similarities. If one of the existing cases showed many similarities with the new one, only one of them were kept and the knowledge extracted of the eliminated case was added to it. The list of the cases studies that were considered for analysis but was filtered out is presented in Appendix 0: Case Studies Lists.

Initial criteria for selecting the cases were established following the rationale mentioned above and fulfilling the following:

- The case is chosen from the academic or the practice field. Each case resembles a complete application that is designed either for research or for a real-world application.
- The cases selected are complete cases published in academic journals. The source of information are mainly articles describing the cases from the point views of their designers and authors.
- The case has clear digital data process and implementation in the design context regardless of the phase or the level of the implementation.
- The case provides a solution where one or more architectural or urban elements are involved.
- The case has one or more technological methods of data integration, analysis and application.

Each case has its context, its data operation's components and significant technological techniques. All the cases utilise data differently to capture and provide certain values. These cases vary in their interactivity and their emergence between physical and virtual environments. There is no specific order in the discussion of the cases. Table 6 shows the selected cases and the domain in which they exist. Table 7 gives a brief description of each of these cases and the data sources.

Table 6 Selected Case Studies

#	Case Study Title	Domain
1	Liverpool ONE Pedestrian Visualisation Project	ICT
2	Chicago Energy Map	Governmental Data
3	Campus Information and Knowledge Modelling	Management
4	Four Chairs and All Others	Product Design
5	Human Behaviour and Spatial Configuration	Office Design
6	Reveal It, My Position	Urban Screen
7	SIG 04	Architecture Machine
8	Hospital Project Using RFID	BIM/Construction

Table 7 Brief Descriptions of The Selected Case Studies

#	Case Study Title	Description	Data Theme	Sources
1	Liverpool ONE Pedestrian Visualisation Project	A project based in Liverpool, United Kingdom, where data is collected through sensors implemented within the Liverpool ONE shopping area to expose pedestrian footfall.	Pedestrian Data	(Red Ninja Studios, 2014)
2	Chicago Energy Map	A governmental project of the City of Chicago, United States. This project provides energy information through an online portal for occupants through various visualisations.	Open Data	(Chicago Data Portal, 2017) (Chicago Energy Data Map, 2013) (Chicago Mayor's Press Office, 2012) (Chicago Mayor's Press Office, 2013)
3	Campus Information and Knowledge Modelling	An academic project based in the Georgia Tech Campus in the United States. This project utilises a proposed information model that is based on both Building Information modelling (BIM) and Geographic Information Systems (GIS) to assess campus planning and management.	Micro Urban Data	(Gomez et al., 2013) (Swarts et al., 2013)
4	Four Chairs and All Others	A generative non-linear design project that utilises data and existing 3D models to propose new designs based on the concept of geometric fusion. The data addresses cultural and social aspects.	Data to Product	(Roman, 2012) (Roman, 2013) (Roman, 2014)
5	Human Behaviour and spatial configuration	An academic project that utilises different methods to collect data about human behaviours to inform the design decision of spatial configuration.	Evidence-Based Data	(Sailer et al., 2015) (Sailer & McCulloh, 2012)
6	Reveal It, My Position	A project that utilises occupants' provided data to project information through public spaces. The project was deployed in Córdoba, Argentina, and Barcelona, Spain	Social Visualisation	(Valkanova, 2015) (Valkanova, 2013)
7	SLG 04	A project that resembles architecture as a machine. It employs an intelligent system (Responsive Framework) which responds to occupants' behaviours and needs, based on specific data exchange. The research project was developed at the Transformable Intelligent Environments Laboratory in the School of Architectural Engineering, Technical University of Crete, Greece.	Responsive Architecture	(Oungrinis, & Liapi, 2014) (Oungrinis et al. 2013) (Liapi et al., 2012)
8	Hospital Project Using RFID	A project that combines the use of Building Information Modelling (BIM) and real-time tracking sensors to manage a construction site.	Operational Data	(Costin et al., 2015) (Costin et al., 2014) (Costin & Teizer, 2014)

The cases are referred to using the numbering that appears in Table 6. These numbers are used later in the analysis and the following chapter.

4.2. The Construction of Concepts through the Case Studies Analysis

The main method that is used to construct the concepts from the case studies is the manual coding of the documents, literature and records. The manual coding is a comprehensive process based on a word-by-word observation and pointing out keywords. The code is a word or a short phrase that symbolically gives a core-capturing attribute of linguistic or visual data (Saldaña, 2009). The coding is achieved Horizontally and Vertically. The Horizontal coding examines each case in its context and relates the concepts from the perspective of that case study. However, the Vertical coding inspects the concepts in all cases together and allows an open coding to take place. The coding is completed based on the Grounded Theory.

4.2.1. The Use of the Grounded Theory

The Grounded Theory develops a theory and a framework that explores the practicality of data-driven architectural operations and applications in business. The framework is developed inductively from the collected data according to the Grounded Theory (Chesebro and Borisoff, 2007).

The Strauss approach of the Grounded Theory is employed. This approach has three coding procedures, which are: Open, Axial and Selective. Three reasons contributed to choosing the Struss approach over the Glaser approach in employing the Grounded Theory. The first reason is that in the Struss interpretation there is a balance between analysing data and utilising formal theory, while the Glaser interpretation focuses solely on the data with no respect to existing theory (Hickey, 1997). The second reason is that the Struss approach has an emphasis on the practicality and the application of the studied phenomena rather than the experience of the researcher (Muller, 2010). The third is the systematic approach of the Struss interpretation and the taxonomy of coding actions (Sikolia, 2013).

The Open Coding delivers categories for the data-driven model in each case. The observed phenomenon is the use of *Big Data* and the *Internet of Things* technologies. The Axial Coding delivers dimensions, concepts and assemblies by relating the established categories from the Open Coding to the sub-categories generated from the Axial Coding through all the cases. This coding delivers a universal data-driven operational model of all the cases. The Selective Coding integrates the categories into the proposed Data-Driven Operational Framework. These three types of coding were not employed in sequence; in fact, the process was overlapping and formed a continuous cycle of shifting between the collected data, the analysis and the insights.

In the Grounded Theory, conducting a literature review about the topic of the research is discouraged. However, a literature review was conducted to foster the process by supporting the researcher to identify what is relevant to this theory in this thesis (Hickey, 1997).

4.2.2. The Grounded Theory Coding Procedures

In this thesis, the theoretical data is recognised from the literature review, which covers the following topics: *Big Data* technology, Value in architectural design and Data-Driven Business Models. This literature review allows the establishment of basic coding categories for the observed phenomena. The coding starts with the collected data from the cases, which establishes the Basic themes. The Open Coding is followed by the Axial Coding then Selective Coding. A continuous coding process on all levels allows saturation of the data. When data is saturated, a core concept is constructed. Figure 27 shows the four types of coding in the Grounded Theory and the relationship between them.

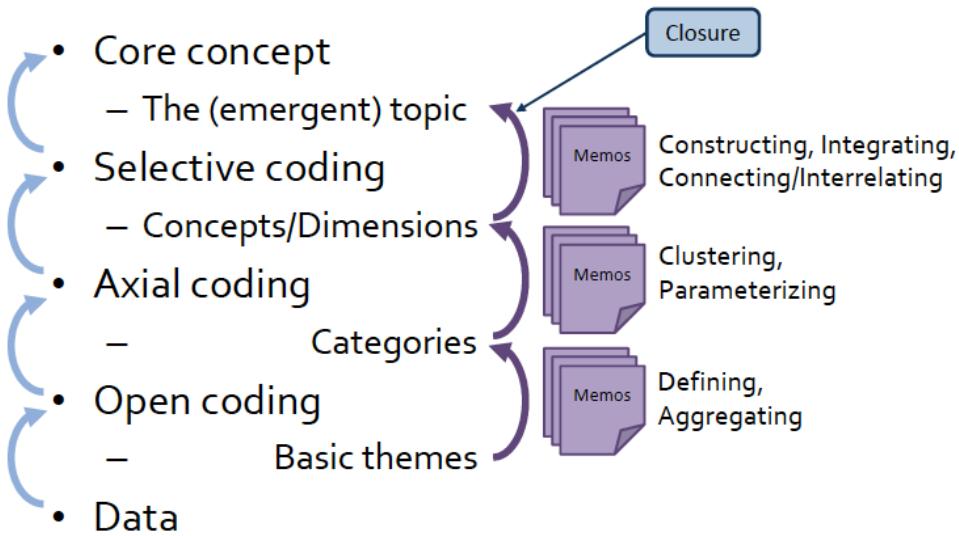


Figure 27 The Coding Procedures of The Grounded Theory (Muller, 2010)

I. The Open Coding

The Basic themes identified from the literature review, as mentioned earlier in Chapter 2: *Big Data* and Architecture, are derived from the Data-Driven Business-Model Framework. Through the Open Coding, it was apparent not all the themes identified from the literature review were relevant. The ones that are relevant and related are Data Sources, Key Activity, Data Offering, Target customer, Revenue model and Specific cost advantage (Figure 28).

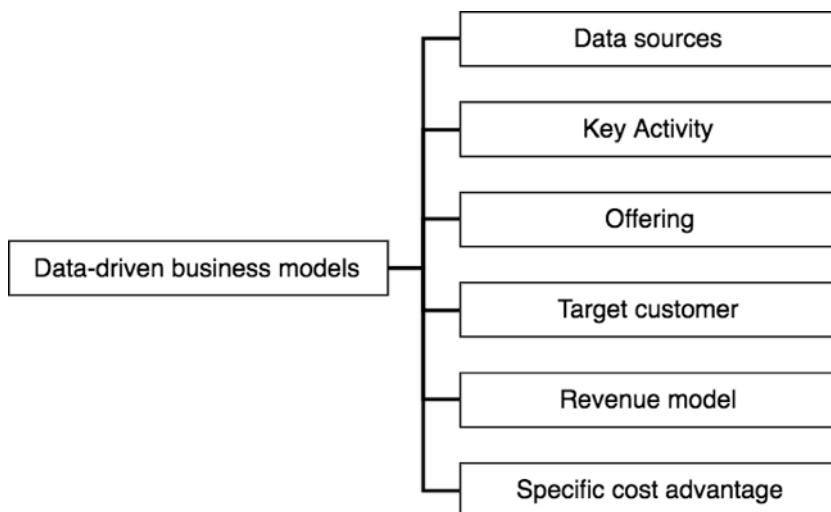


Figure 28 The Basic Themes Derived from The DDBM Framework (Hartmann et al., 2014)

These are universal components of data-driven operational models that are employed in other industries. These components allow a basic understanding of the

data-driven business and form a base to start the coding process. These components are Data Sources, Data Handling, Data Offering, Architectural Value Proposition and Architectural Business Channel. Figure 29 shows these components. Table 8 defines each of these categories.

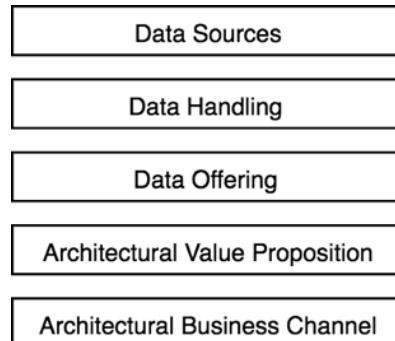


Figure 29 Case Studies Open Coding Themes

Table 8 Case Studies' Open Coding Themes

Data Sources	The source of the data that is stored or streamed. The source is identified by the type and hierarchy of stored and streamed data.
Data Handling	The computational process used for acquiring, processing and applying data.
Data Offering	The output of the Data-Handling process in the specific context of the case.
Architectural Value Proposition	The values realised from the case. These values are applicable in an architectural context; they have the potential to contribute to the value systems in architecture, and possibly have an impact on the AEC practice.
Architectural Business Channels	The business strategy that the AEC can adopt. This strategy includes the channels for promoting values in the built environment.

The Open Coding was achieved by coding the collected data of the case studies word-by-word, line-by-line and event-by-event continuously in relation to the basic identified themes (Key Activity, Data Offering, Target customer, Revenue model and Specific cost advantage). This continuity allows the emergence of the proposed components. Figure 30 shows an example of the Open Coding procedure.

Key Activity	University College London (UCL). Grounded in thorough and rigorous research of both a client's organisation and its space, the process provides new levels of insight into the social and spatial functioning of a business.	study of occupancy, movement and interaction brings to light how people actually use the space. These methods are combined with spatial analysis techniques using DepthMap software ²⁶ which assesses the performance of the workplace layout revealing the potential of space to integrate or segregate people, and thus how it facilitates collaboration.	Data Source Key Activity Key activity Architectural Value - Social
Data Offering	The process often starts by working with senior management to establish a clear understanding of the issues and challenges currently faced by the organisation, and to set the overall measurable benefits to be delivered by the project. Often clients do not know exactly what they need from a space; at the same time, not many companies are actively collecting performance metrics themselves. Essentially, the first step of the approach is to create a more informed and systematic brief for the project. A series of structured one-on-one 'stakeholder' or head of department interviews then helps to clarify the current and desired future working practices of different parts of the organisation as well as informing an understanding of the interactions and collaboration networks in the business. An online staff survey is used to explore what individuals need from their workplace, how satisfied they are and how well they perceive it currently matches up to the task. Last but not least, an observation	Through the layering of this evidence, and in conjunction with the client, strategic recommendations are made for an ideal space, and new ways of working within it. A spatial strategy is then developed that includes a schedule of total recommended space requirements, as well as a masterplan (see Figure 1), which maps key spatial relationships between departments. These provide an extensive and detailed brief that:	Data Handling/ Combining Architectural Business Channel!! Architectural Value / Use Architectural Business
Data Offering		<ul style="list-style-type: none"> • defines the fundamental principles of a workplace design that is tailored to the exact needs of an organisation; • allows an organisation to change (if desired); and • increases the satisfaction, happiness and wellbeing of employees. 	Architectural Value Proposition
Data Sources			Architectural Value
Key Activity			Architectural Value / Image
Data Offering			Architectural Value / Use / Psychological
Data Sources			
Architectural Value - Use			
Architectural Value - Psychological			

Figure 50 An Example of The Open Coding Achieved for Case Study 5 Collected Data (Sailer et al., 2015)

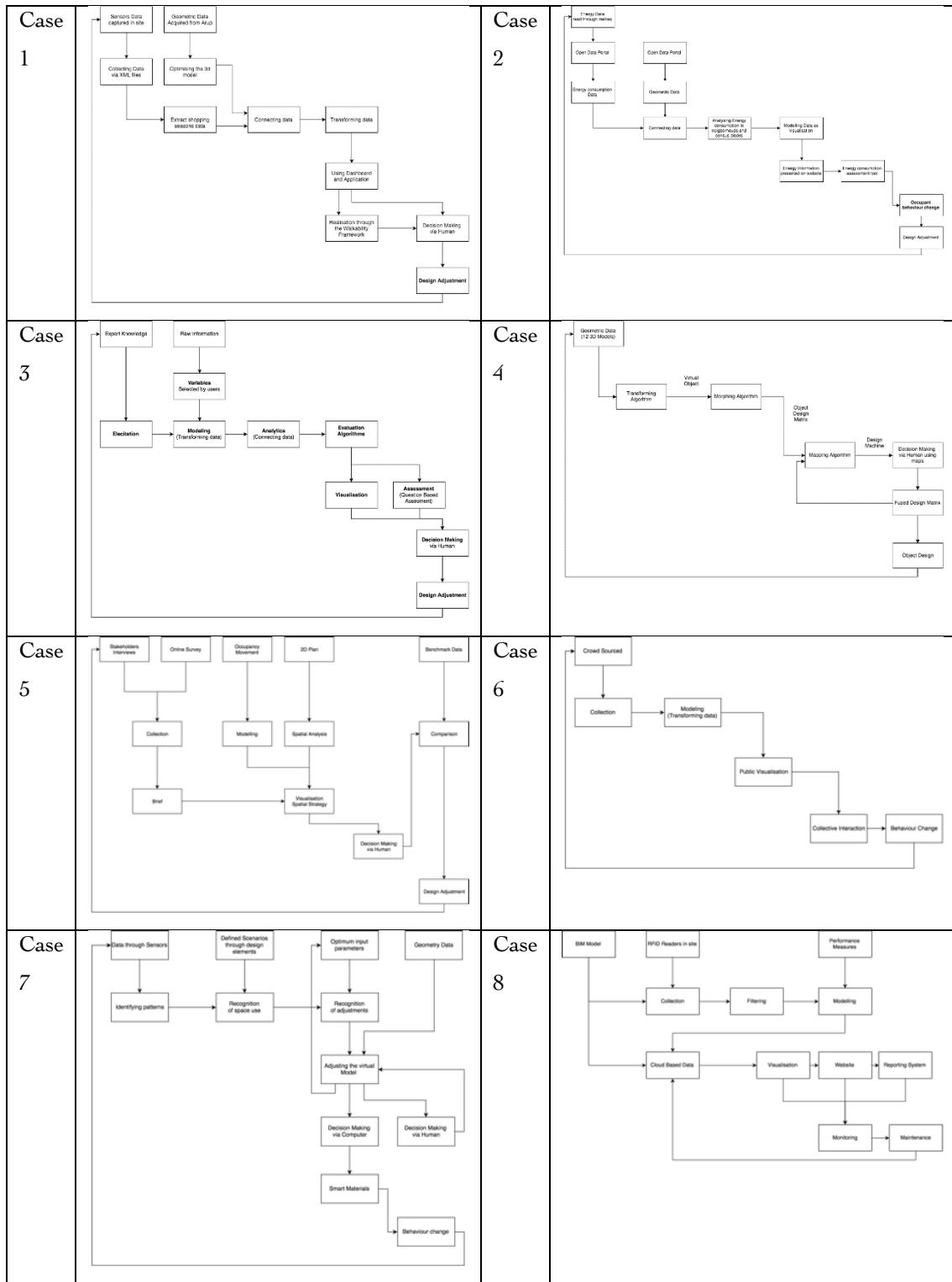
Through the Open Coding certain codes are extracted from the available literature, these codes allow the emergence of different categories which represent the Axial Coding. These codes are represented in a table for each case study. The Open Coding leads to extracting information of the Digital Value. The repetition of certain type of values in the coding affects how the Digital Value Equaliser is presented.

II. The Axial Coding

The Axial Coding relates categories to subcategories, specifies the properties and dimensions of each category, and reassembles the categories to give coherence to the emerging analysis (Charmaz, 2014). In this coding procedure, the aim is to connect these components together based on the operational process that takes the input and gives the output. This connection reveals the data-driven architectural process. The Axial Coding has two procedures, Horizontal and Vertical. The Horizontal Axial Coding is presented in the previous chapter for each case study with a diagram that represents the Data-Driven operations. The Horizontal Axial Coding allows the understanding of the data-driven model in each case through a grounded understanding of the following: how the data-driven components are connected on an abstracted level across different categories; how these connections and categories are ordered; how humans intervene within the process; how value is created within the process; how the process continues. The Axial Coding of the process was not possible without the value coding initialised in the Open Coding

procedure. Table 9 presents the Horizontal Axial Coding recognised for each of the cases.

Table 9 The Horizontal Axial Coding of The Case Studies Processes



The Vertical Axial Coding relates all the processes together and allows a universal understanding of the overall data-driven process in architecture. Figure 31 shows

the Vertical Axial Coding. Four different data processes are identified: Collection and Gathering, Aggregation and Processing, Analytics, and Modelling. These processes are interrelated in a specific order. Each one of these processes allows the specific intervention of data through a specific application. An example of this is the Collection and Gathering process: it simply allows direct decision making by humans. It also provides an output in the form of information, and, finally, it serves as an input for the subsequent process of Aggregation and Processing. These processes are defined later in this chapter.

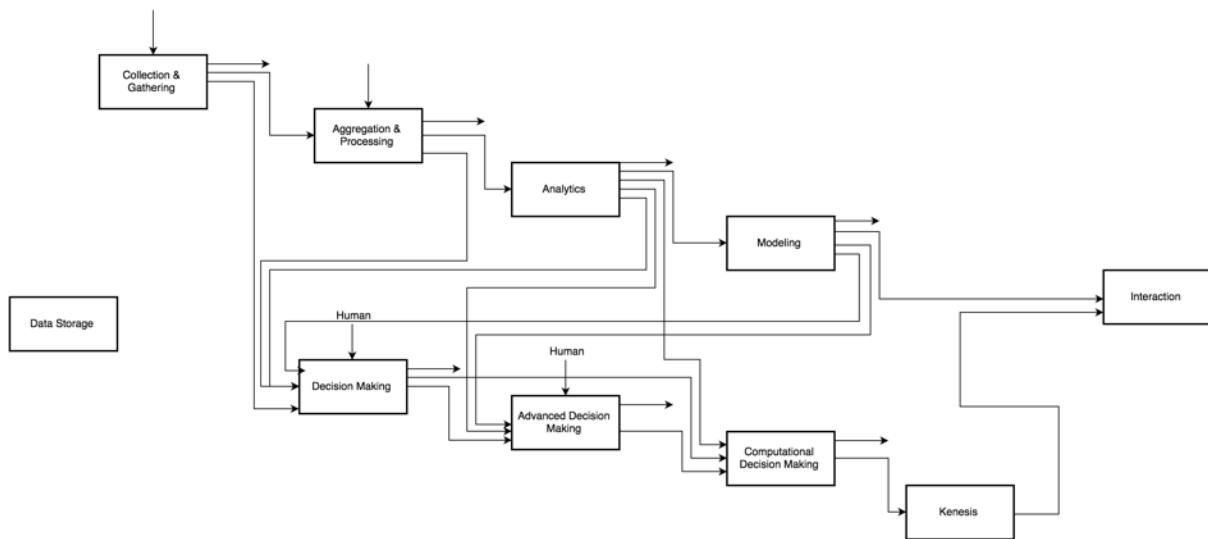


Figure 51 The Data-Driven Model in the AEC

The Axial Coding allowed the realisation of the following:

- The processes of data handling are cumulative and occur in a specific order starting with Data Collection and Gathering, then Aggregation, applying Analytics and ending with Modelling. However, there is no order for how data can be connected and utilised after handling.
- Two levels of data mapping are realised. One is seized by human involvement, and the other is seized by a computer.
- There are two levels of decision making (Basic and Advanced) that a human can take in a data-driven environment. Advanced Decision Making requires a greater level of data handling.
- The Basic Decision Making is more subjective and based on the level of clarity in the collected data and the competence of the human. The Advanced

Decision Making is more objective as the data is clearer and less human involvement is required.

III. The Selective Coding

Selective Coding as a process specifies possible relationships between categories which have developed in earlier coding procedures (Charmaz, 2014). Also, it allows the constructing of ideas to achieve a conclusion. The Selective coding in this research allows the emergence of the data-driven operational core components. Four components are identified: Peripheral Data, Recognition, Intervention and Application. Together, these define the data-driven architecture framework that is described in detail in Section 5.1 below.

IV. Core Concept

The core concept that can be obtained from the Grounded Theory analysis in this thesis is divided into two parts. The first part is identifying the level of data intervention in architecture and the second is the impact data-driven operations has on the AEC. These two concepts are identified later in Section 5.2 and Section 5.3 below.

V. Summary

In the previous sections, the various coding procedures of the Grounded Theory that are used in this research are discussed. Each procedure as mentioned earlier contributed to a specific output and each following output depends theoretically on the previous one. A theoretical sampling and a constant comparative analysis to achieve data saturation were applied through the entire analysis.

4.2.3. Validation and Discussion

In order to check if the research results are satisfactory and sufficient, certain validation criteria are required. Since the research was executed based on a Grounded Theory methodology, suitable criteria from such a methodology are required. In the following section, an evaluation of the proposed Data-Driven Operational Framework is carried out according to the general criteria of the Grounded Theory research proposed by Glaser (1968). These criteria are Fit, Relevance, General, Workable and Modifiable, as follows:

1. The theory should fit the substantive data and be continuously sharpened by constant comparison (Fit).
2. The theory should be comprehensible and appeal to all involved in the area of study (Relevance) and extend the relevance of the study beyond the substantive area of the researcher (Generalisability) (Glaser, 1998).
3. The theory's concepts and the way they are related and integrated should sufficiently account for the hypotheses (Workability).
4. The theory can be modified by new data (Modifiability).

I. The Data-Driven Operational Model Framework validation

The Operational Framework is developed for the purpose of implementing data and data-driven approaches in architectural design and business in support of the concepts that developed throughout the research. The framework employs theoretical operational models which allow business models to emerge. The verification concentrates on the consistency and completeness of the operational framework. The Grounded Theory must be assessed from the internal logic of the methodology and not from an external criterion from other research paradigm and methodologies (Charmz, 1994). The developed framework was used to analyse the design process of a test case. The aim of the analysis was:

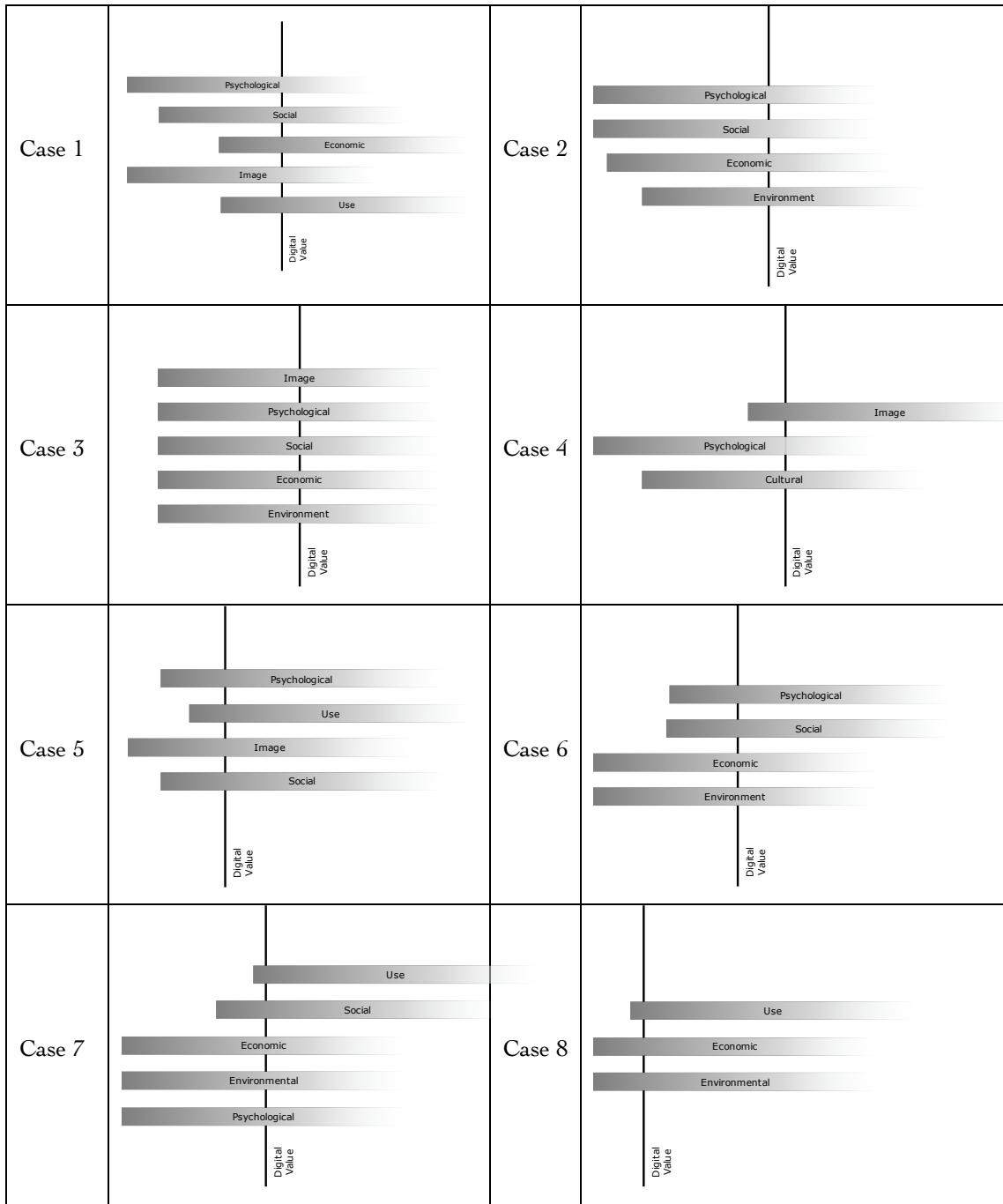
- Test the fit of the Data-Driven Operational Framework on the new case data, and whether the framework adequately expresses the pattern in the process.
- Verify the applicability of the Data-Driven Operational Framework in the case-specific context and whether it explains how the problem is solved if there are many variations.
- Confirm that the framework captures the actual concerns of the business.
- Test whether the analysis can capture new information and allow the emergence of new data-driven concepts to be amended in the Data-Driven Operational Framework.

4.3. The Digital Value Equaliser

Utilising the value coding of the case studies, a universal Digital Value Equaliser was created; it shows the value coding of the cases. Figure 32 shows the Universal

Digital Value Equaliser. The Universal Digital Value Equaliser was achieved by combining all the Digital Value Equalisers produced for each case.

Table 10 Value Coding of The Case Studies



All the obtained Digital Values found in the case studies are listed. They match all the value types that MacMillan (2005) proposed and of which has been discussed in Chapter 2. The colour gradation represents the role of the Digital Value as a transforming medium from information to an application. The appropriate

utilisation of the digital value in the Data-Driven Operational Model requires an appropriate application that is based on more information. Decomposition refers to the possibility of re-obtaining information from the application to generate further values using the Digital Value.

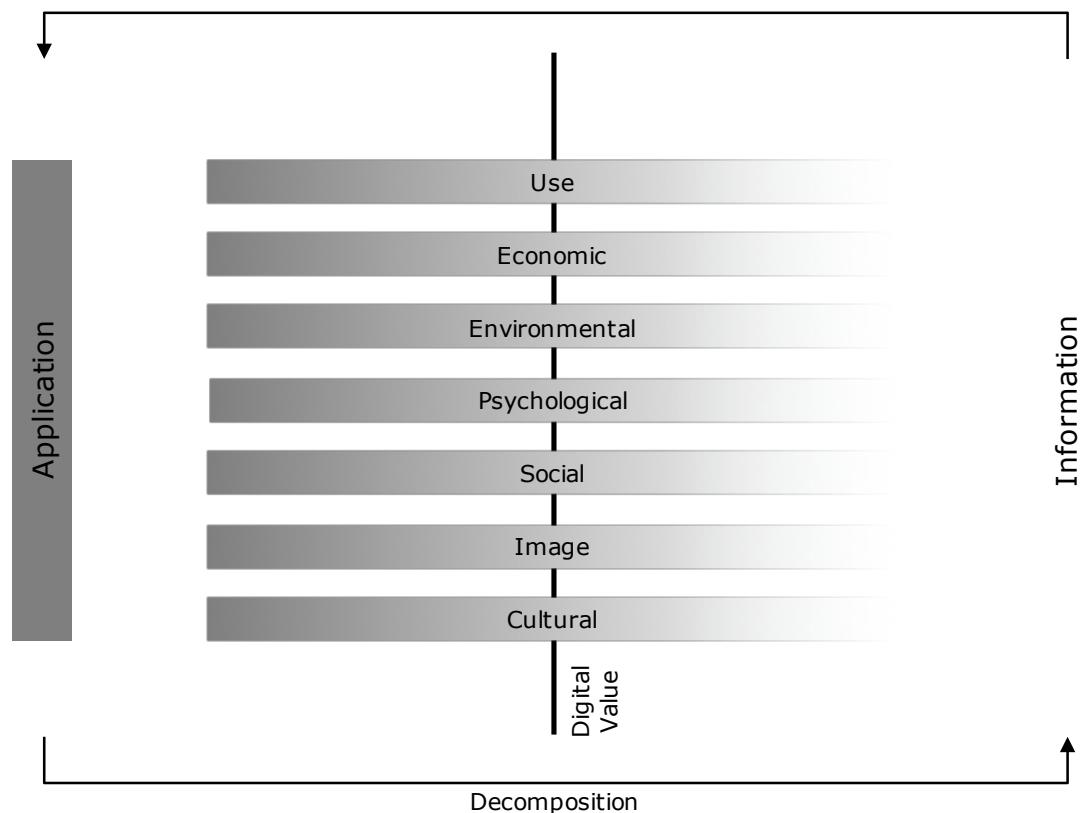


Figure 52 Digital Value Equaliser for Data-Driven Operational Models in Architecture

4.4. The Case Studies

In this section, a description of each case through the Open Coding categories (Data Sources, Data Handling, Data Offering, Architectural Value proposition, Architectural Value Proposition) is accomplished. Each case has a table for the Open and the Axial codes achieved in the coding of the literature. Also each case is represented with a Digital Value Equaliser and a diagram of the Data Operating Process.

4.4.1. Liverpool ONE Project (Case Study 1)

This project is the only case where the analysis is conducted based on Participant Observation. The type of participation that is employed is Moderate Participation.

This participation allows the researcher to be involved in the project while keeping a distance in order to remain objective about the case (DeWalt and DeWalt, 2010).

This participation was achieved by the researcher engaging in specific stages of the project for three weeks and then leaving the project and remaining an observer. The researcher's involvement in the project was based on his 3D modelling skills.

The observation of the project was an opportunity provided by a postgraduate training scheme that is sponsored by the University of Liverpool and offered by a Liverpool-based technological company (Red Ninja Studios). This project is part of an extensive project delivered by Red Ninja Studios entitled: iNSIGHT. The objective of this project is to develop a 3D interactive model to present consumer habits to retailers in one complex in Liverpool (Liverpool ONE). This project allows Liverpool ONE's managers and business partners to gain enhanced consumer insights for the Liverpool ONE area (Red Ninja Studios, 2014).

The Project had three stages. The first is developing a 3D model for Liverpool ONE, which the researcher has completed. The second is projecting data relating to pedestrian movement on the developed 3D model, and this stage was completed by the company's computer programmer. The third stage is visualising the interactive model using a gaming engine (Unity) and providing a virtual experience using 3D glasses. The second and third stages did not include the researcher as part of the project.

I. The Open Coding

a. *Data Sources*

The Liverpool ONE retail development has an established system of three monitoring networks: Bluetooth sensors, sensors for calculating pedestrian numbers through mobile devices and a Closed-Circuit Television (CCTV) system. These systems are intended to be used by the security personnel to maintain safety and provide protection to visitors in the area.

The system is not designed to deliver any further analytical information. However, the sensors are generating a massive amount of data daily. This generated data has no further use and is destroyed. The Liverpool ONE project made use of the data

streams from the sensors which calculate the pedestrian numbers. These sensors utilise mobile devices to do the count.

The sensors are capable of sensing the Wi-Fi signal emitted from pedestrians' mobile devices as they are passing. As one pedestrian passes the range of a sensor, a signal is recorded as a tagged entry in an XML file. The file is saved temporarily in the sensor's memory, and then the data is collected later by the monitoring company. A legal agreement was signed in order to allow Red Ninja to access such data. The data from these sensors is the first source of data input in this case. This data is considered Active as it happens in time and actively changes.

Another source of data input is the 3D model of the Liverpool ONE area. The 3D model represents a different type of data. This data is geometric. This geometric data is considered Static. The reason for considering it static is that this data does not change and it remains constant through the data implementation. The 3D model hosts the other type of data and acts as a background for the Active data. The initial 3D model was acquired from an Arup engineering consultant.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 11 Open Codes of the Data Source of Case 1

Open Codes	Words from texts	Axial Codes
Data Source	Sensors detecting pedestrian movements 3D Model of Liverpool ONE	Active External Data Static Internal Data

b. Data Handling

The data handling has two stages due to the two different data inputs. Handling the Active data represented in pedestrian movements is the first stage. The method that is employed to track pedestrian movements through sensors is Hitchhiking[°]. The Hitchhiking method considers the location as a domain of interest rather than the

[°] See Appendix 2: Terminologies for terminology

pedestrians' entity. The Hitchhiking method provides privacy as a pedestrian's entry to the sensor's coverage zone is recorded anonymously (Tang et al., 2005). The Hitchhiking method enables the sensor to register the location of any device that has an active Wi-Fi receiver. This registered location is added to the XML file, which contains data about the position of each mobile device that is entering the area. The XML files of each sensor are inputted into a processor which analyses the data and transfers it to two applications. One application has the 3D model and makes use of each imported position from the XML files to create a point in the 3D model. Each point is assigned a sim (a virtual actor or a simulated human agent). These actors are then synchronised with the 3D model coordinates to simulate human movement in the virtual 3D model. The other application performs another analysis by initiating a comparison between the numbers of people leaving and entering the area to provide information about the flow, pedestrian pace, average zone occupancy and average visitor interval. This information is processed through pre-defined algorithms in the application, and the information is streamed to a 2D dashboard and displayed on the 3D model for the representation purposes.

The other stage is handling the Static data represented in the 3D model. The initial 3D model was attained from an Arup engineering consultant. This model is a collection of files that represent the whole area of Liverpool city centre as 3D masses. These masses have the buildings' volumes (footprint extrusions) which are achieved through block modelling (Batty et al., 2000). The blocks have no textures or identity; this makes it hard for the viewer to distinguish the represented buildings. The researcher's contribution is preparing the 3D model meshes focusing on the targeted area (Liverpool ONE), then texturing these blocks through image-based texture-mapping using a 3D modelling software program (3Ds Max), and, finally, optimising the 3D model and exporting it for the use with gaming engines. The texturing was achieved using in-field photos and Google Maps' street view service (Figure 33).



Figure 55. Screenshots from The Liverpool ONE 3D Model in Different Phases During the Modelling Process (Blocks, Textured, Night Shot, Day Shot)

The importance of the texturing process is that it provides the architectural details that are necessary in order to understand the virtual environment in the 3D model. Textures make the 3D model more appropriate to accommodate the pedestrian data and allow the application's user to locate the pedestrians while having a reference to the real environment. It is important to mention that the pedestrian data (Active data) in this process was aggregated in later stages. Pedestrian data was filtered to save effort and time. Since the sensors are generating data daily throughout the year, it is hard to apply the whole tracking process for each day of the year as this consumes tremendous computing power and time. As mentioned earlier, this project targeted retailers and businesses; thus, the data was filtered to show pedestrian data during shopping seasons and off-seasons.

In summary, the Active data is generated on the site by pedestrian movements, and then it is acquired in data batches. Afterwards, the data is filtered, processed, analysed and, finally, modelled virtually. The data-handling platform is a computer desktop located in the company.

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 12 Open Codes of the Data Handling of Case 1

Open Codes	Words from texts		Axial Codes
Data Handling	Extending the Sensors Network. Data Generation through Location Based. Collect. Process. Generate New Data.	Privacy	Generation Collection Processing Generation

c. Data Offering

The data, in this case, has different levels of offering. However, according to the specific context of the project, it provides information about the following attributes: pedestrian flow, footfall timeline, average zone occupancy and average visitor duration across the high street in the Liverpool ONE area. The consumer insights are offered for definite times of the year through a dashboard and a 3D model. The provided information gives Liverpool ONE retailers and business owners insights about consumer habits during certain seasons; this information supports their decision making and gives them suggestions for the following seasons. Figure 34 shows the dashboard developed by Red Ninja Studios.

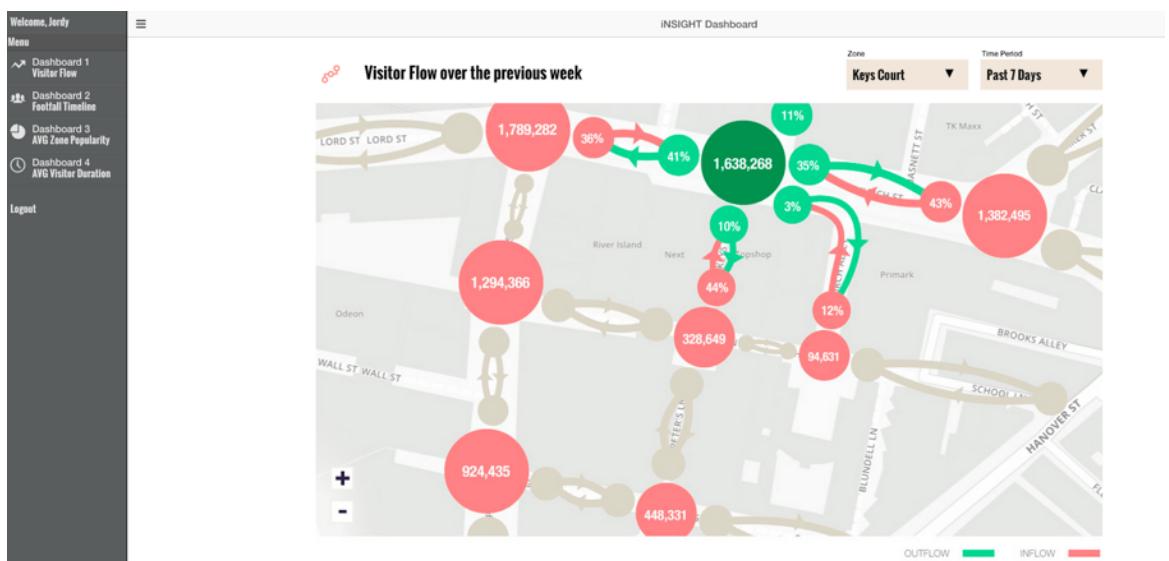


Figure 34 The Insight Dashboard for the Liverpool ONE Area Visualising Footfall (Red Ninja Studios, 2014)

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 13 The Open Codes of the Data Offering of Case 1

Open Codes	Words from texts	Axial Codes
Data Offering	High Accuracy Location-Based tracking.	Input - Technique
	Shopper Movement.	Output – Information
	Real-Time Data.	Input
	Analytics.	Analytics
	Footfall Timeline (2)	Output – Information
	Visitor Duration. (2)	Output – Information
	Return Consumers information.	Output – Information
	Visitor Flow.	Output – Information
	Zone Popularity.	Output – Information
	Consumer Behaviour.	Output – Information
	Insight (3)	Output – Information

d. Architectural Value Propositions

The sensors are generating the pedestrian data regardless of the project; however, this data was wasted and not effectively utilised. The project makes use of this data to provide deep insights about the Liverpool ONE area's space performance through applying some analytics and algorithms. The information includes real-time pedestrian flow, footfall timeline, average zone popularity and average visitor duration across the high street. Such information aims to reflect the circulation and the walkability of the space.

One valuable acquisition of such data in architecture can be achieved through implementing a theoretical urban framework as part of assessing the project. The walkability framework proposed by Ewing and Handy (2009) provides a basis for such an approach. The overall walkability in the city depends on three factors. These factors are the physical features, the urban design qualities and the individual reactions. The physical features are determined by the space's physical measures and dimensions such as sidewalk width, building height, etc. The urban design quality contains the attributes obtained from the human perception of the space such as scale, complexity, etc., while the last factor is about the human interaction

with the space (Ewing and Handy, 2009). Figure 35 shows the walkability framework.

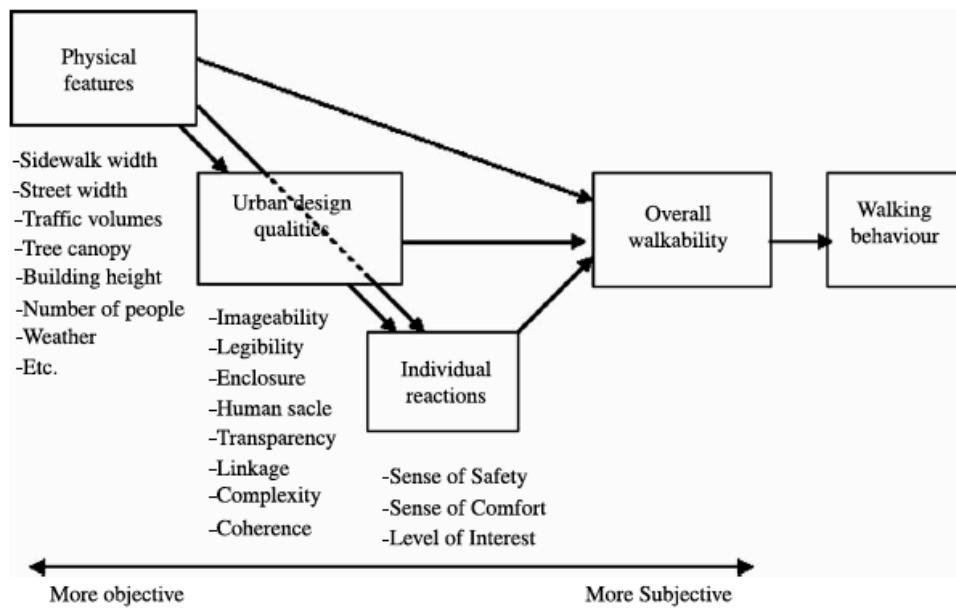


Figure 35. The Walkability Framework (Ewing and Handy, 2009)

The textured 3D model provides information about the physical features; if the model is representing a real, definite location, then it is offering a platform for simulating reality. The data about the human activity in that area is available through trackers and sensors. Connecting these two data inputs shows the pedestrians' walking behaviour in that location, which is used immediately to assess the overall walkability and the urban design qualities. Using such a tool, the architect assigns relationships between pedestrians and buildings and has the opportunity to enhance the possibilities of positive social interactions based on evidence.

According to this, an Active data-connected 3D model which is assessed through architectural frameworks provides better insights and direct information about the architectural and urban qualities of space in comparison to Static one. An architect or an urban designer utilises such a tool to assist the decision-making process. This tool has the ability to test future design scenarios based on the evidence of people's behaviour. The tool is considered a live representation of the interactivity between people and buildings in the city.

The pedestrian circulation, whether continuous or not, can be redesigned and monetised in time by redesigning the urban physical features and monitoring the human reaction through the data-connected 3D model.

In-time (live) data positioning systems introduce the idea of synchronised space visualisation – a space that has time as a working factor, a space that is linked to buildings and other elements in the cities where virtual and reality can be interpreted to assess architectural properties and human interaction and behaviour in time. Bringing an architect or an urban designer into this data integration system is necessary to provide architectural and urban value. The architect is able to specify the parameters that inform the design decision. This project shows that data implementation has potential to provide visualised-based and simulation-based applications and decision support tools.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of the case.

Table 14 The Open Codes of the Value Propositions of Case 1

Open Codes	Words from texts	Axial Codes
Value Proposition	Analytics Dashboard (2) Consumer Super-App	Application – Dashboard Application – Mobile App

e. *Digital Value Equaliser*

Using the Digital Value Equaliser, a diagram of these values is presented in Figure 36. The figure shows the emergence of five values which are enabled by the digital value; these values are Psychological, Social, Economic, Image and Use. Also, the Digital Value Equaliser shows the degree to which each value emerges and appears.

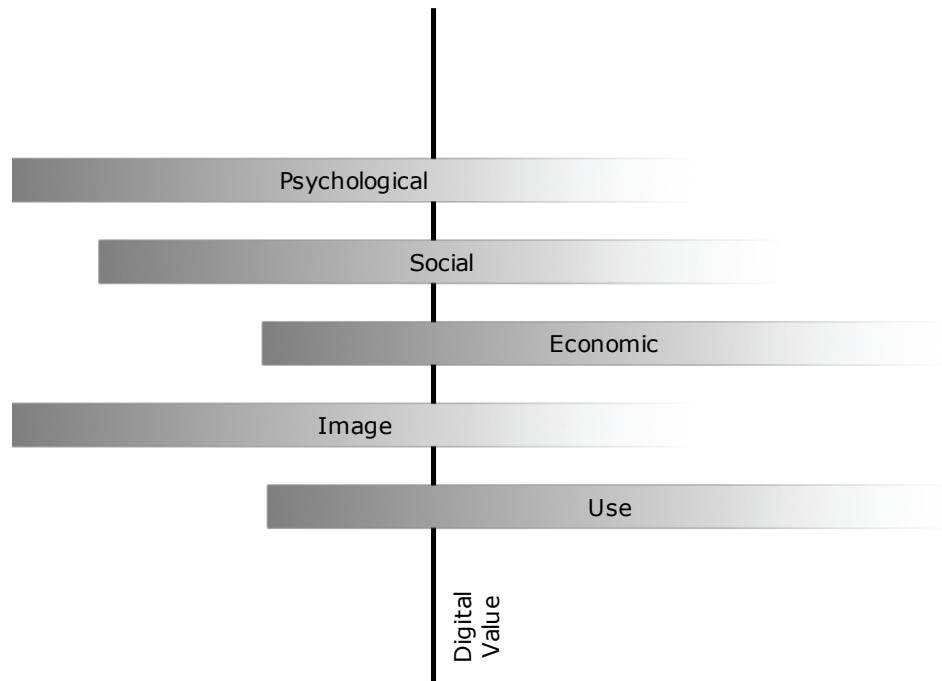


Figure 36 Case Study 1 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 15 The Open Codes of the Architectural Value of Case 1

Open Codes	Words from texts	
Value	Use	Enhance Consumer Profiling (2) Personalised Shopping Experience. Optimise infrastructure. Justify marketing spend.
	Economic	Cost Effective

f. Architectural Business Channels

There are two identified channels, one is through the different use of data insight, and the other is through the established connection between clients and occupants.

The data insights combined with other architectural design frameworks and principles provide a tool to support design decisions. Clients can use this information to propose, remove or redesign certain architectural elements or buildings. They can analyse the performance of a particular area in the city based on pedestrian flow and can obtain information about pedestrian evacuations and reactions to certain events and factors. Also, data accumulated over many years has the potential to be used to simulate future scenarios based on historical events. This

simulation predicts pedestrian movements through the proposed changes to space, and this can be utilised as a future evidence-based design. This channel requires the service to be added to the existing design contracts.

The other channel is the connection between the decision makers and the occupants (the pedestrians) in public areas through location-based services. This connection enables a passive contact between the stakeholders and the inhabitants. Such an approach provides a new method of communication. This connection can be enhanced through the use of crowdsourcing services to collect direct data from pedestrians along with passive data. The data shows different patterns and provides useful information to then be examined and translated into design actions.

II. The Data-Operating Process Analysis

Utilising the data implementation methods along with the Walkability framework provides a deeper understanding of the case. Figure 37 represents this Data-Operating Process Analysis.

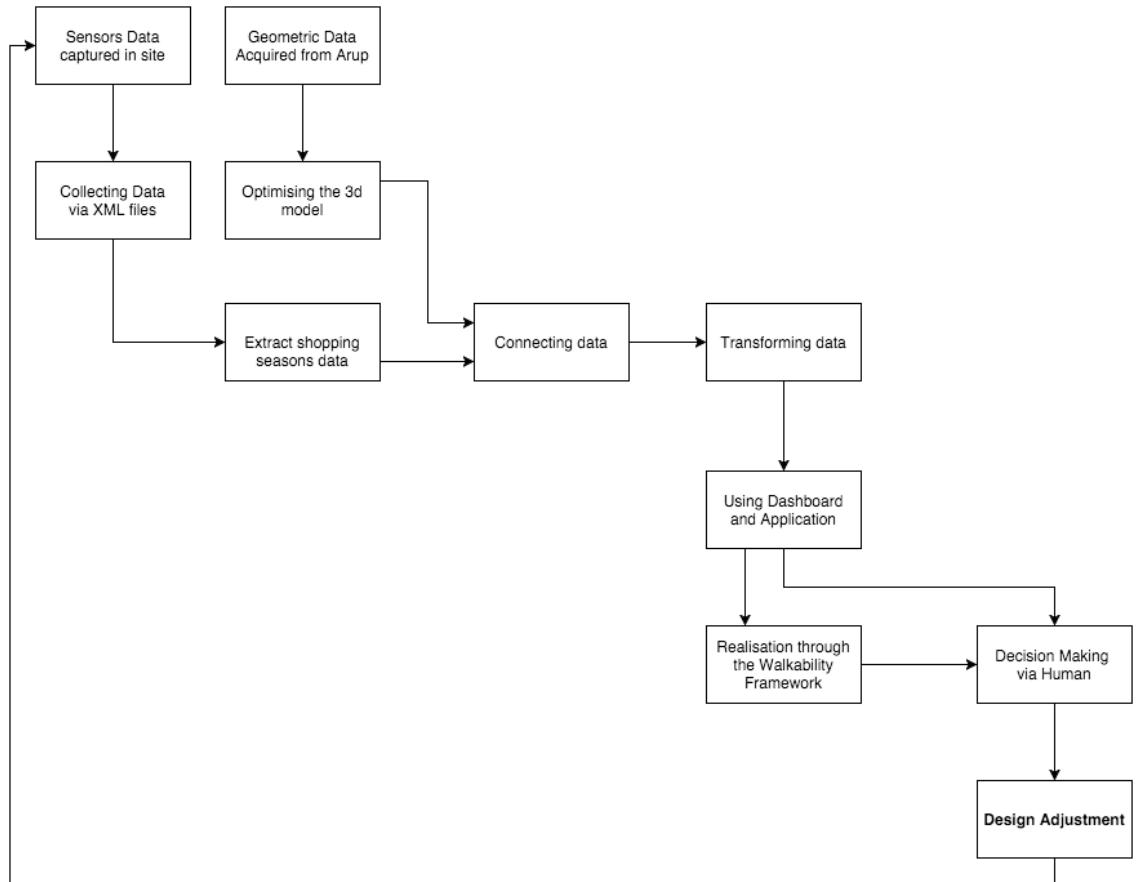


Figure 37. Liverpool One Case Study Data Process Analysis

III. Concerns

There are two points of concern in this case. The first is technology limitations and the second is privacy. With regard to technology, the project sensors count the pedestrians as they are passing a specified zone. And, since the mobile devices are monitored anonymously using Hitchhiking, the sensors are still incapable of recognising each singular unique device. The sensors will record the same device as multiple entries if the device holder (pedestrian) passes by the same sensor more than once. The method could be more efficient if each mobile device was tagged with a personal identification number during the sensing phase.

The other concern is privacy. Privacy is a major issue when dealing with data on human movements and daily living. The Hitchhiking method that is employed in the data implementation process is an example of the existence of other technical methods that protect the privacy of the participants and provide sufficient results for data users at the same time.

IV. Case Footnote

This concludes the end of the analysis for the motivating case study where the researcher was involved as a participant. The following cases will be analysed from the available literature and materials, focusing on the coding produced by the Grounded Theory.

4.4.2. Chicago Energy Map and Open Data Portal (Case Study 2)

This case has been chosen for the use of open governmental data in the data application. The Chicago Energy Map is an Application Programming Interface (API) created to use the data provided by the City of Chicago Open Data Portal. This initiative is a collaborative effort between different institutions. The Chicago Energy Map is a tool used to visualise the consumption of natural gas and electricity in residential neighbourhoods and blocks of the City of Chicago in 2010. Occupants can access the tool through the online web address: <http://energymap.cityofchicago.org/>. The website provides datasets for the City of Chicago. This data demonstrates the performance of the city, the services and the facilities. The portal is dedicated to supporting the accessibility to governmental data as a step to encourage the development and the creation of innovative tools that engage and serve the community besides serving as an informative dashboard. The Data Portal provides sample tools and tutorials for developers to facilitate the development of applications.

I. The Open coding

a. *Data Sources*

The analysis aims to examine the data sources in the two platforms: The City of Chicago Open Data Portal and the Chicago Energy Map.

The Chicago Energy Map makes use of the open data offered by the City of Chicago's Open Data Portal. The Open Data Portal offers more than 400 machine-readable and searchable datasets (Chicago Mayor's Press Office, 2012). This data has been collected from various companies, authorities and sectors in Chicago. The data is available in the following categories: Administration and Finance, Buildings, Community and Economic Development, Education, Environment and Sustainable

Development, Ethics, Events, Facilities and Geographic Boundaries, FOIA, Health and Human Services, Historic Preservation, Parks and Recreation, Public Safety, Sanitation, Service Requests, Transportation. These categories offer an overall taxonomy for the database on a city scale. However, the data formats available are: API, Blob, Calendar, Chart, External, Filter, Form, Map and Tabular. The different formats allow developers to integrate the appropriate format into their applications.

The Chicago Energy Map uses three types of data as an input: Geographical data categorised as Environment and Sustainable Development, which is provided in a map format, 3D Geometric data categorised as Buildings, which is provided in external format, and, finally, Energy-Use data categorised as Environment and Sustainable Development provided in a tabular format. The data source for this case is external and the data can be identified as Fast Data.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 16 Open Codes of the Data Source of Case 2

Open Codes	Words from text	Axial Codes
Data Source	Geographical data 3D Geometric Data Energy Use Data	Static External Static External Active External

b. Data Handling

The data is managed to generate visualisations. The geometric data from the map provided the base to represent the energy consumption patterns that are showing as 3D Blocks. The Chicago Energy Map delivers two levels of visualisation of the city. The first level is a 3D abstract representation for the city census based on energy (electricity and gas) consumption (see Figure 38, left). The second is accessible when choosing a specific Census Block[°] from the first representation and it is a 2D colour-shaded map for the neighbourhood blocks (see Figure 38, right); this represents an informational map for a block's energy consumption.

[°] See Appendix 2: Terminologies for terminology

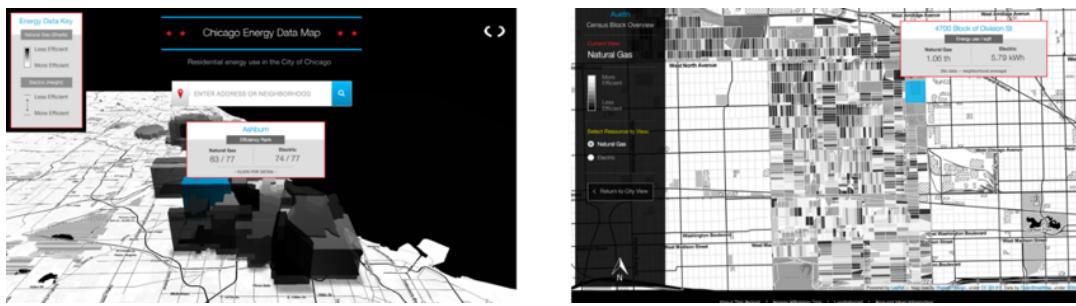


Figure 38 City of Chicago Energy Map. Left: First Visualisation Level. Right: Second Visualisation Level (Chicago Energy Data Map, 2013)

The overall energy consumption data is acquired from energy meters installed in residents' houses. This data is acquired in tabular formats. It is collected, analysed, classified and presented in two levels. The first level is at the Census Block scale, and the second is at the neighbourhood scale.

These levels were chosen to protect the privacy of Chicago residents as the scale does not reflect each individual's consumption. A Census Block map of the City of Chicago was used as a base for this data implementation. A 3D mass for each Census Block was modelled based on the energy consumption data. The height of each census mass model represents the level of energy consumption. Each Census Block is linked to the neighbourhood map. This neighbourhood map hosted the data of the energy consumption on the neighbourhood level. A gradation of black and white colours represented each block's energy efficiency. The two levels of representation are programmed for web interactivity and have a Tooltip feature. In addition to this, an Energy Efficiency Tips tool is programmed into the same website to raise the knowledge and awareness of energy efficiency and advise the residents of cost-saving tips.

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 17 Open Codes of the Data Handling of Case 2

Open Codes	Words from text		Axial Codes
Data Handling	Data Analysis Data Visualising	Privacy	Analysis Modelling

c. Data Offering

The web-based application is programmed to give information on two different overviews: city and neighbourhood (Figure 38). This information is given through interactive visualisation. In addition to the visualisation, the website provides an “Energy Efficiency Tips” application interface.

The visualisation displays two types of energy use through an interactive representation. Different graphical representations are applied to show the consumption of electricity and natural gas. The height of each 3D block indicates the electricity use while its colour shade indicates the natural gas use. The mouse hover tooltip appears when highlighting an object to provide numeric information.

The objective of the visualisation is to provide the online user with information regarding the energy consumption patterns in the City of Chicago on two overviews to indicate how the neighbourhoods function in comparison to each other.

The “Energy Efficiency Tips” is a platform for occupiers to share tips and reviews to promote efficient energy use. These reviews have guidelines that support taking measures and encourage individual home improvements. Also, the platform provides customised suggestions for users that promote behaviour changes and actions to reduce energy consumption. This tool has a calculator that displays an estimated annual cost saving for each applied change (Figure 39). Both tools offer a self-regulating behaviour impulse.

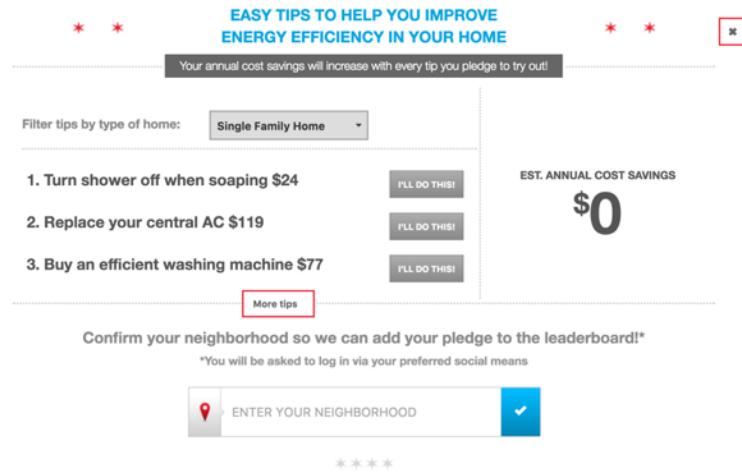


Figure 39 The Energy Efficiency Tips Tool on The City of Chicago Energy Map (Chicago Energy Data Map, 2015)

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 18 The Open Codes of the Data Offering of Case 2

Open Codes	Words from text	Axial Codes
Data Offering	Energy Use (2)	Output - Information

2. Architectural Value Propositions

The architectural value proposed in this case affect both the individual and the collective users of architectural spaces who have access to the data application.

The main proposition is utilising visualisations to affect occupants' behaviour, which affects how the space performs. This case shows how collective data about a building's performance and energy consumption can be presented to occupants. Buildings act as data-generating sources, and this data is utilised in an application interface that connects a single occupant to their neighbours through information. This shared experience promotes a collective behaviour change based on interest in achieving environmental sustainability and bounded by the location.

The secondary proposition is represented by the "Energy Efficiency Tool Tips" offered by the web application. The tool allows every occupant to conduct independent measures that affect the building envelope collectively. The measures

vary from changing pipes to installing insulation. These changes affect the energy performance of the building. Having architects monitoring these measures allows an in-time understanding of the effect of such actions on the performance of a single space and the impact of that space on the neighbourhood.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 19 The Open Codes of the Value Propositions of Case 2

Open Codes	Words from text		Axial Codes
Value Proposition	Visualisation Interactive Interface		Visualisation Interface

e. Digital Value Equaliser

Figure 40 shows the Digital Value Equaliser for this case. As seen in the figure, the focus is on the environmental values. However, the case has the potential to utilise psychological, social and economic values.

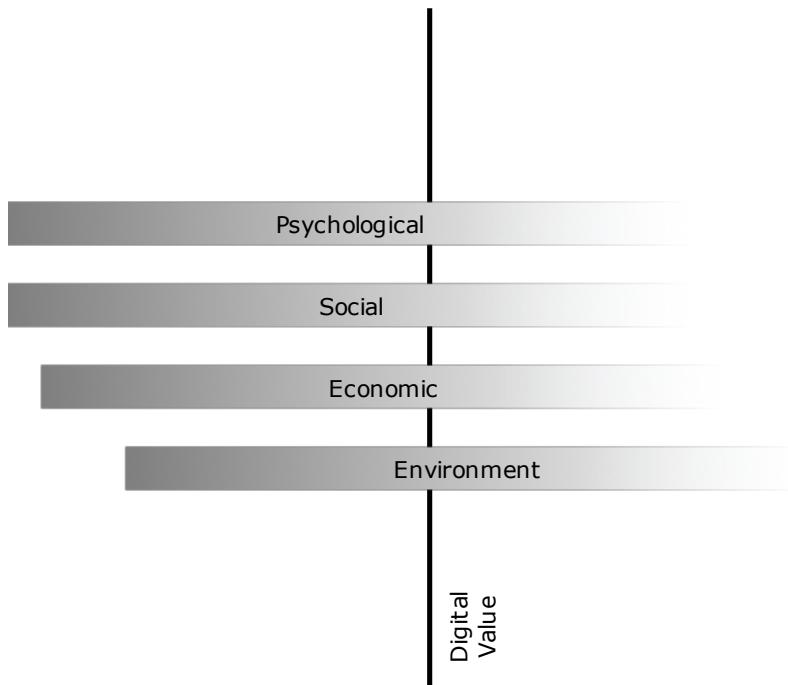


Figure 40 Case Study 2 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 20 The Data Codes of the Architectural Value of Case 2

Open Codes	Words from text		Axial Codes
Value	Use	Increase Home Efficiency	Application
	Social	Neighbourhood Efficiency Retrofitting the City Program	Output - Information
	Economical	Saving Money (2)	
	Environmental	Reduce Building Energy Requirements Increase Energy Efficiency	
	Psychological	Increase Awareness Collective Behaviour-modification	

f. Architectural Business Channels

The important channel that this case provides is the establishment of a direct connection between architects and occupants. This channel allows Post-Occupancy Evaluation and Urban Design Decision Support. Giving architects access to such a tool for their designed building provides an opportunity for a direct post-occupancy evaluation based on the energy consumption through the use of the grid. This tool also supports an assisted energy control to help in designing buildings based on the exploiting current neighbour configurations and performance. This extensive monitoring can be added to the design contract.

This use of data provides live statistics on the energy consumption of buildings and allows a comparative approach in Urban Analysis. This information is valuable for both new developments and neighbourhood renovation plans.

This case represents an example of smart grid initiation, which is a component of the smart city movement. The smart grid enables an intelligent infrastructure for utilities and objects using digital technologies. This technology allows the intelligent network to react and to adapt according to changes in the local use.

II. The Data-Operating Process Analysis

The following diagram (Figure 41) represents the case analysis:

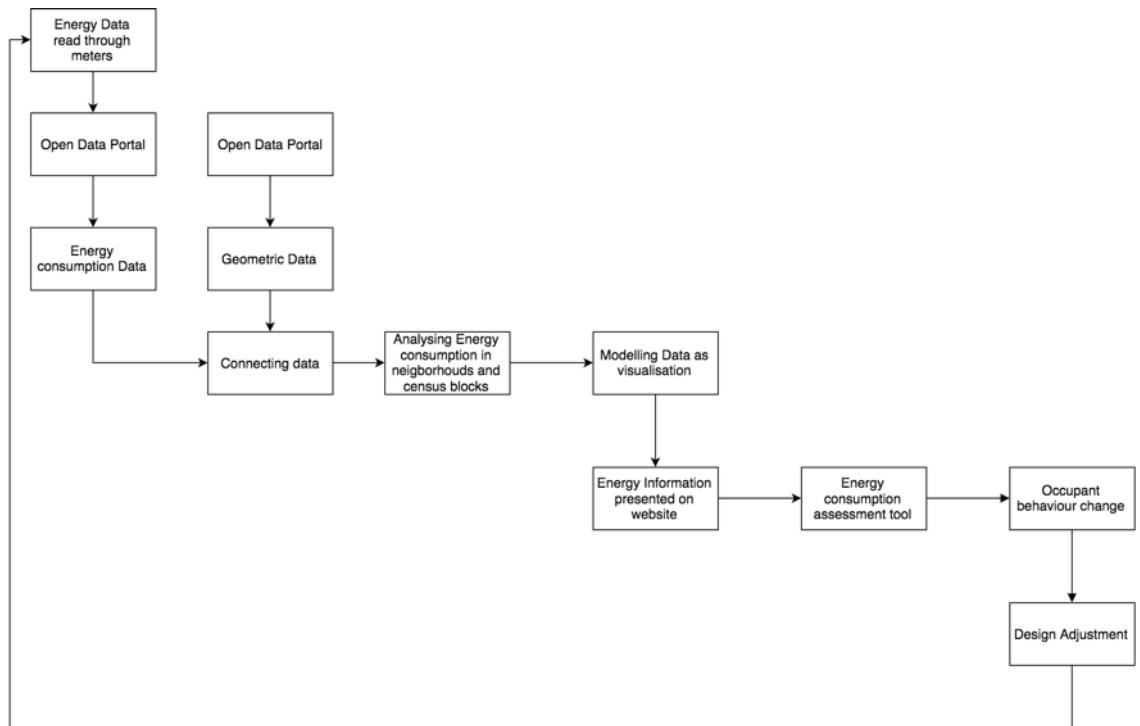


Figure 41 Chicago Energy Map Case Study Data Process Analysis

III. Case Footnote

The concept of publishing such a data portal is not exclusive to the City of Chicago. The open data government is part of a significant trend that promotes transparency. For example, the United Kingdom government is offering a similar web portal under the domain <http://data.gov.uk/> as an initiative for opening and making data available for everyone. What distinguishes the City of Chicago portal from any other city's data platform is the emphasis on making the datasets available for everyone in various accessible formats; it even provides free online and offline toolkits for developers and makers to develop new tools and applications.

4.4.3. CIKM for Georgia Tech Campus (Case Study 3)

The Campus Information and Knowledge Modelling (CIKM) represents a method for the use of data in the built environment in an intermediate urban scale that includes the buildings and the landscape (Gomez-Zamora and Swarts, 2014). The case makes use of two built environment information frameworks: BIM (Building Information Modelling) and GIS (Geographic Information System). There is a growing interest in the integration of BIM and GIS in the AEC industry (de Laat and Van Berlo, 2011); the reasoning is that the two frameworks differ in attributes

and scale, and combining the two approaches together provides comprehensive quantitative and qualitative information for use within a campus context. A new framework was developed for the Georgia Tech campus to conduct landscape scenarios to support design decisions.

One reason that makes this case distinctive is that it considers the built environment and the landscape together. Gómez et al. (2013) indicated some software packages that have been developed to support landscape design. The software can be categorised into three types: planning, providing landscape information, and drawing and visualising. These tools focus on the landscape aspect and ignore the buildings, isolating the landscape from the buildings.

Another reason is the utilisation of different data sources and the focus on proposing a framework to implement external expert knowledge from landscape designers into the design tool.

I. The Open Coding

a. *Data Sources*

The data is based on two defined models, Information models and Knowledge models, as described by the developers. The Information models represent the direct raw data obtained from available planning documents, satellite imagery, databases and observation of land use, such as the geometric data, locations and attributes of existing landscape elements such as trees. The Knowledge models refer to the information obtained from experts and users, such as design constraints, objectives and operations. This information is extracted from five primary sources: Facilities Inventory and Classification Manual (FICM), Campus Master Plan, Urban Planning Studio Teaching, Appointed Case Studies and Expert Interviews. The Knowledge models require different methods of knowledge transformation and representation. However, the Knowledge models' data is connected to data from the Information models and it is programmed to work with it.

It is important to define each source in order to understand how it contributes to the use of data in this case. The FICM is a manual that is designed to assist the institution in maintaining and creating a facilities inventory database. The database

is a directory for all inventories, and provides information about space utilisation, future planning, decision making, and reporting for institutional comparisons (Cyros and Korb, 2006). Also, the FICM offers space classification and evaluation. The Campus Master Plan contains the guidelines for the university campus design, and it has the overall design objectives that are categorised into qualitative and quantitative objectives. The Urban Planning studio teaching is an attempt to implement the knowledge generated in an educational design studio project into practice. The projects that were given to the students were placed in a university context. The students proposed several solutions for each design problem. These solutions were used and applied as sets of parametric design solutions in the Knowledge Model. Finally, the Case Studies and Expert Interviews were used to identify the gaps and validate the proposed approach by applying the acquired knowledge to a real campus renovation scenario; this application allows changes in the data structure and the addition of new unidentified constraints. The data sources can be identified as external except for the Urban Planning Studio Teaching, and were acquired from different available sources. Table 21 shows the different data sources for the Knowledge Model in this case. This case has a complex data type which can be identified as Semi-Structured.

Table 21 Data Sources of the Knowledge Modeling the CIKM Case Study

Data	Source
Facilities Inventory and Classification Manual	External
Campus Master Plan	External
Project at Urban Planning Studio	Internal
Case Study	External
Expert Interviews	External

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 22 Open Codes of the Data Source of Case 3

Open Codes	Codes from Text			Axial Codes
Data Source	Information Models	Integration of Geometric Representation of	Raster. Vector.	Input - Geometry

		objects and their attributes		
	Knowledge Models	The variable Constrains Goals Operations		Input - Parameters
	FICM Landscape Master Plan Planning Studio Interviews Case Study			Input

b. Data Handling

The data acquired from various sources was categorised into Expert Knowledge and Raw Data. The data is offered to users using a graphical user interface (GUI). This categorisation allows two levels of model representation, Knowledge Model and Information Model, as mentioned previously. The data contained in the Information Model is directly modelled to visual representations using two different computer graphic formats: Raster and Vector.

The Knowledge models are represented through diagrams, graphs and charts as they are more complex and require evaluation algorithms and stochastic^o models. The evaluation models are based on the variables selected in the Information Model. Knowledge models were identified through four knowledge-elicitation techniques: existing documentation, observation of experts collaborating on a specific case study, analysis of tasks of the specific case study, and interviews with experts and users (Gomez-Zamora and Swarts, 2014). Figure 42 shows the two different Model Levels explained earlier.

^o See Appendix 2: Terminologies for terminology

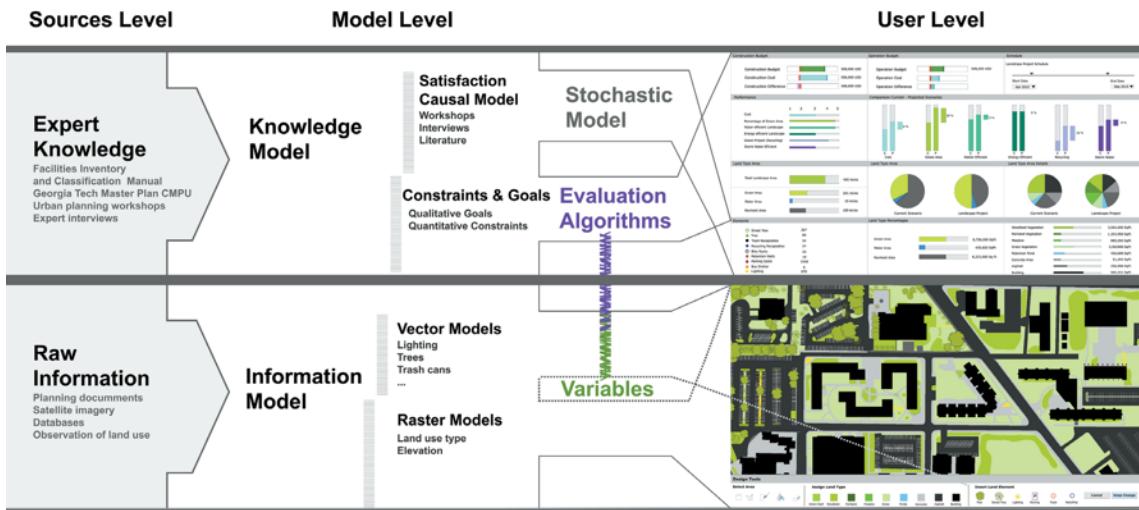


Figure 42 The Two Model Levels in The CKIM (Gomez-Zamora and Swarts, 2014)

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 25 Open Codes of the Data Handling of Case 5

Open Codes	Codes from Text	Axial Codes
Data Handling	Integrates BIM and GIS. Data Analysis. Data Processing. Data Classification Data Recognition. Data Storage. Data Retrieval, Data Translate. Data Connection.	Analytics Analytics Processing Aggregation Intervention Input Intervention Modelling Analytics

c. Data Offering

The data application offers quantitative and qualitative information in a table-top interactive screen entitled CLIM “Campus Landscape Information Modelling”. This tool supports the direct real-time collaboration of different stakeholders by assessing landscape design and planning through identified scenarios. The assessment is offered by a dashboard that represents information about the campus, such as real-time graphical updates, quantities of existing elements, project information, and objectives’ evaluation. Each of these components has its sub-classification. The other qualitative assessment is offered through parametric questions that are programmed from the quantitative information to provide answers that support decisions.

To summarise, the output is an interactive visualisation interface that enables the tool's user to interact with the data through a list of commands. This interface replaces the need for a dashboard. The CLIM interface tool is distinguished from other dashboards and reporting applications for the following two reasons: the first is the focus on proposing an approach to measure the qualitative aspects of design planning, whilst the second is the use of scenarios to provide answers for predictive situations.

The various data sources and the chosen methods to elicit data and translate it into a question-based inquiry provide a unique tool that supplies answers. Questions are generated by using a framework that is identified by question type, static variables, temporal variables, and a list of goals and constraints.

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 24 The Open Codes of the Data Offering of Case 3

Open Codes	Codes from Text	Axial Codes
Data Offering	Support Collaboration. Storage and Retrieval of Alternative Design or Scenarios. Display Spatial and Temporal Representation	Application Intervention Application - Interface

d. Architectural Value Propositions

The analytic dashboard is not new technology to the AEC industry. Lamptey and Fayek (2012) mentioned different types of management reporting systems in construction, and dashboards have originated from the development of these management reporting systems. Dashboards are used in informing project progress and managing building performance. Rasmussen, Bansal and Chen (2009) suggested various beneficial uses for dashboards in business, and these benefits apply to architecture. Some of these benefits are: providing a visual representation of performance measures, evaluating efficiency in the project, revealing new trends in data and processes, and lining up strategies and overall goals.

The integration of informative dashboards and Computational Aided Design tools in real time provides a unique approach for architects to design, monitor and

maintain their designs. This method has more potential to add various types of values to the built environment, such as Image, Psychological, Social, Economic and Environmental.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 25 The Open Codes of the Value Propositions of Case 5

Open Codes	Codes from Text	Axial Codes
Value Proposition	Dashboard User Interface Design Strategies	Application – Interface Output

e. Digital Value Equaliser

Figure 43 represents the Digital Value Equaliser for this case. The Digital Value Equaliser for this case is revealed to be neutral because the value coding of this case did not show any differentiation between the extracted values.

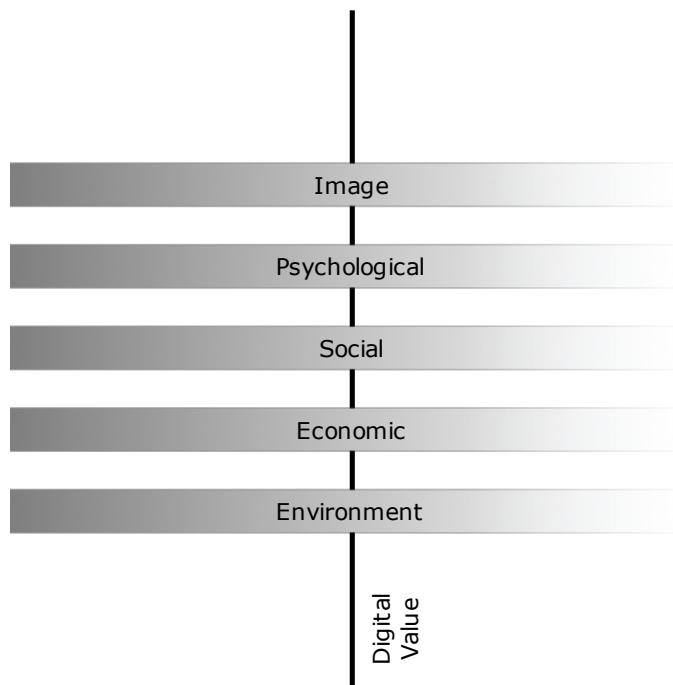


Figure 45 Case Study 5 Digital Value Equaliser

f. Architectural Business Channels

One of the main contributions of this case is that it proposes the need for a technological methodology and platform for information management of the built

environment intermediate urban scale. This could be achieved through establishing a data ecosystem for the built environment that connects data from buildings with data from urban environments. This data ecosystem will allow the sharing of data sources and analytics between various buildings while acknowledging the difference in context and locations.

Another significant channel which this case provides is the utilisation of students' work and institutional knowledge of design studios by taking the academic-based knowledge and applying it in practical cases. The students' work in urban design studios provides a valuable source of data. It is possible to document the students' design solutions and provide them as parameters. An open-source online platform could be dedicated to providing students' solutions for architects to use. This value resembles an expansion approach to involving universities in practical projects on a worldwide scale.

II. The Data-Operating Process Analysis

Figure 44 shows the analysis of the data processes in this case.

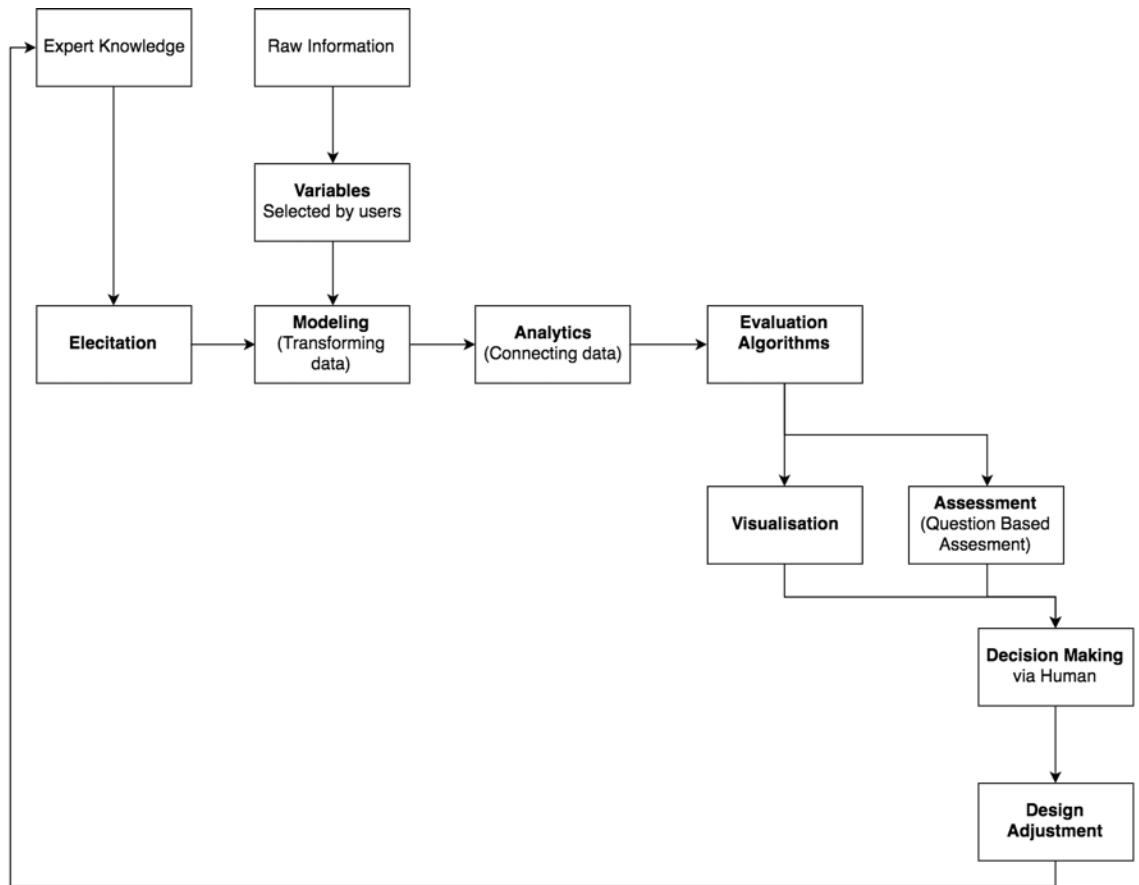


Figure 44 The Campus Information Knowledge Management Analysis

III. Case Footnote

This case highlights the role of institutions in providing applicable design knowledge as discussed earlier.

This case provides a remarkable knowledge taxonomy. The extracted knowledge is structured using Bloom's taxonomy of Factual, Conceptual, Procedural and Meta-Cognitive Knowledge (Gomez-Zamora and Swarts, 2014).

4.4.4. Four Chairs and the Others (Case Study 4)

This case proposes an approach to a nonlinear design development utilising data. This design approach is applied to a chair. The case study experiments with the possibilities of design beyond its physical entity, extending to reach contemporary social and cultural phenomena. This effort was carried out by Miro Roman from the Future Cities Laboratory (Roman, 2013). This case was selected for its different method of implementing data in design.

Although the product is only a chair, architects have been designing chairs for a long time. The Museum of Applied Arts and Design Cologne held an exhibition in 2012 dedicated to architect-designed furniture. According to the museum, architects were the first furniture designers in the early 20th century (Labarre, 2012). The architect's design of a chair reveals the architectural style that s/he favours. The chronological evolution of this design provides an opportunity to tell a narrative about the development of architecture itself.

This case follows the Latin philosophical expression: "ex nihilo nihil fit", which means nothing comes from nothing. It understands design as an open set of possibilities which are reacting to different cultural phenomena. It emphasises the process of digital recycling, which is the process of circulating, accumulating and integrating information and data on chairs in new design methods (Roman, 2013). This case presents a methodology that can be implemented at any scale of architectural design.

I. The Open Coding

a. *Data Sources*

The case uses a complete library of chairs as the preliminary data source, focusing on three main characteristics: geometric, spatial and historical importance. The library of chairs is created from 3D models existing in an online 3D models' library (Sketch Up 3D Warehouse).

The data source is an open source that is available free of charge for architects and designers who use the accompanying 3D modelling tool (Sketch Up). Utilising this 3D models' library is an original idea and sets a novel approach for this case. The historical importance of the selected chairs was added later, based on available online references.

The main data source is considered external and acquired through open sources. The main type of data is Geometric and is supported by text data. The data can be identified as Dark Data.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 26 Open Codes of the Data Source of Case 4

Open Codes	Codes from text		Axial Codes
Data Source	Existing Designs	Thonet's Chair Wire Chair Panton Chair Ghery's Wiggle Side Chair	Input – Geometry Aggregation
	Open 3D Library	Geometry	Input - Geometry

b. Data Handling

The first phase is collecting, standardising and preparing data. Twelve 3D models of chairs are selected from the 3D online library. The reason for limiting the number of selected chairs to 12 is due to the limitations of the computer power and to provide more efficient controlled results.

Two initial technical criteria were applied. The first is that all 3D chairs must fit in the same bounding box. The second is that the vertices of the 3D meshes for each chair are equally distributed throughout the model. These criteria allow the standardisation of the geometrical data of the chosen chairs.

The second phase of data handling focuses on data computation and analysis. The computation is performed in three steps using algorithms. The first algorithm is a transforming algorithm that is applied to the models' meshes. This algorithm transforms the Polygon Mesh into a Voxel-based[°] object. A one-dimensional array list defines the Voxel-based object. The objective of this step is to turn the designs into unified comparable computer datasets. The second algorithm is an algorithm for morphing the chair based on the Principal Component Analysis. The Principal Component Analysis is a computer technique to reduce the dimensionality of a large multivariate dataset (Jolliffe, 2002). The objective of this step is to compress the data size and simplify the computer description. The third step is an algorithm for Mapped Morphing. This algorithm allows the mapping of nonlinear transformations for the chair design. The transformation permits the fusion of three

[°] See Appendix 2: Terminologies for terminology

different chairs through a red green blue (RGB) map. The result of applying this algorithm is a Voxel-based objective that can be analysed again.

The third phase of data handling is visualising the datasets through the use of the Marching Cubes Algorithm and generating 3D print-ready Watertight[°] meshes.

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 27 Open Codes of the Data Handling of Case 4

Open Codes	Codes from text		Axial Codes
Data Handling	Data Fusion Mapping Transformations (2) Analysis Manipulation Merging Generation Normalise Data Applying Algorithm (3) Computing Recycling	Voxelisation Morphing Mapped Morphing	Intervention Analytics Modelling Analytics Analytics Analytics Output Processing Analytics Processing Processing

c. Data Offering

The case aimed to explore the data-driven procedural design approach in shaping an object. According to Roman (2012), this case is an exploratory study that highlights the importance of perceiving design through three aspects: Design, Theory and Technology.

This case manipulates existing data to provide new applicable data that is utilised in design information. In this case, the data manipulation occurs at the geometry level. Also, combining this data with 3D Printing technology allows the creation of a new product.

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 28 The Open Codes of the Data Offering of Case 4

Open Codes	Codes from text		Axial Codes
Data Offering	Design Genealogy Sum of Ideas Infinite Varieties	Objects over coding cultural and historical space-time relations	Intervention Output Output

d. Architectural Value Propositions

The possibility of digitising forms and representing them as datasets provides an excellent opportunity for design innovation because it allows faster and easier format to exchange design information. This representation will be referred to as Object Design Matrix. The Object Design Matrix is a computer-generated matrix that describes an individual object in a set of numeric values; this description provides a meaningful digitised vocabulary of the object's geometrical properties and defines the behaviour of its components and includes metadata. The case builds on this understanding by also introducing the concept of Design Fusion, which is the possibility of creating new designs by merging existing designs together. The Design Matrix and Design Fusion are allowed using Algorithms.

This method is not new to design, especially exploratory design, but what is new is the use of 3D models that are available through an online open-source library (Sketch Up 3D Models Warehouse). These models are crowdsourced, created by users. The models provide an excellent source and a reference for generating Design Matrixes.

The definition of the Object Design Matrix is correlated with the definition of the BIM Object (Ibrahim et al., 2004). However, The BIM is exclusive to be used in a BIM environment, while the former is *Big Data* and the *Internet of Things* compatible. That is because of the datasets format and the wider application.

This whole process can be applied to all stages of architectural design. There are plenty of 3D architectural models that represent architectural designs online. These models offer the possibility of providing a Design Matrix that can be used by other architects. Unifying the architecture models using a Design Matrix format allows

the opportunity for new Design Fusions. Figure 45 shows different design fusions for chairs.

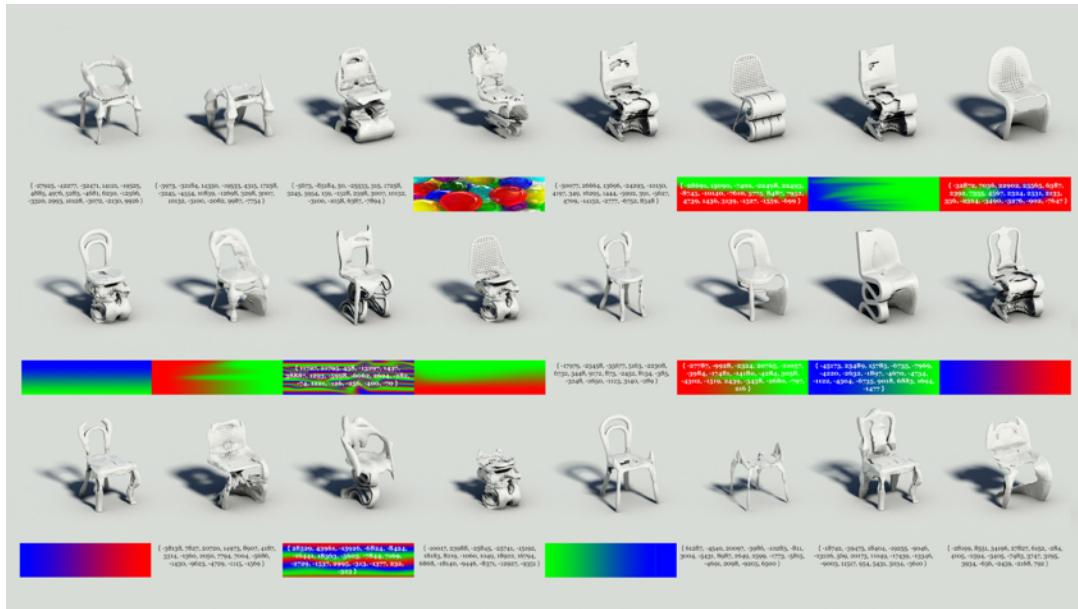


Figure 45 Design Fusion for Chairs

The values implemented in the resulting product in this case are inherited from the original pre-existing designs that are fused together. The value is emphasised through the transformation process and based more on Image and Culture than on other values.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 29 The Open Codes of the Value Propositions of Case 4

Open Codes	Codes from text	Axial Codes
Value Proposition	Generate New Designs	Output

e. Digital Value Equaliser

Figure 46 shows the Digital Value Equaliser for this case.

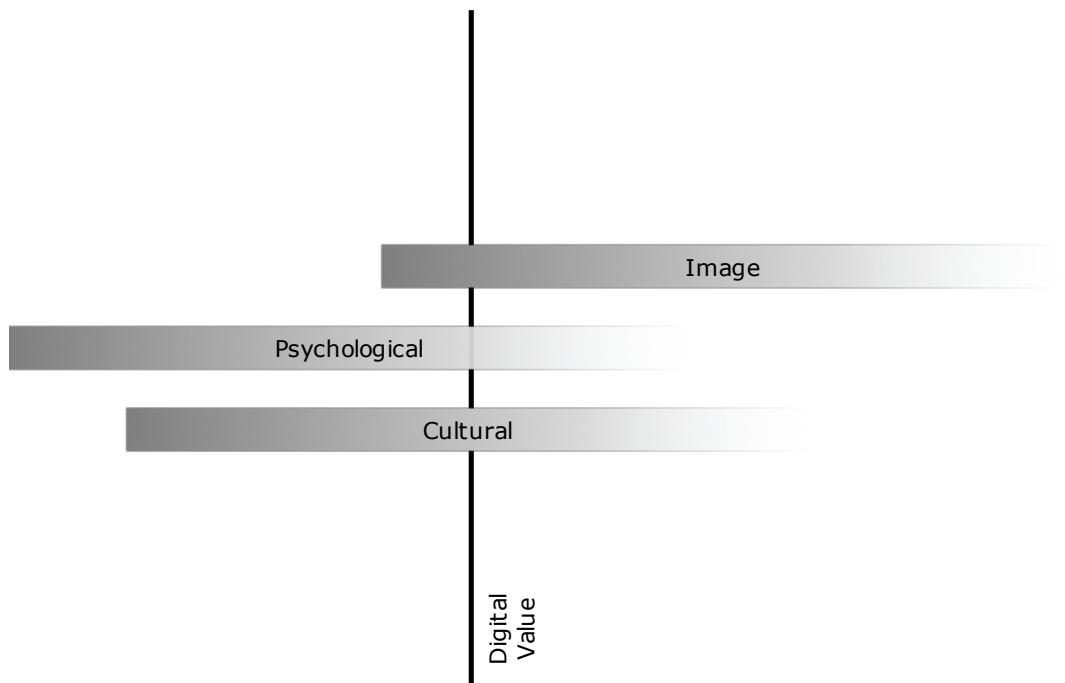


Figure 46 Case Study 4 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 30 The Data Codes of the Architectural Value of Case 4

Open Codes	Codes from text		Axial Codes
Value	Image	Create New Design	Output
	Cultural	Create analogies Create Stories Create Narratives	Output
	Psychological	Fertilize viewer's active participation	Intervention

f. Architectural Business Channels

Architects can offer their designs as Design Matrixes through web-based libraries, allowing them to be reused by other architects and designers. The Design Fusion creates new values and stimulates creativity. Although the built environment is contextual and this context is specific to each design, the Design Matrix can be developed to be intelligent on the design components scale. This intelligence allows the components to react, adjust and adapt to any alternative context.

This channel provides a new business revenue for architects by involving them in the creation of such a matrix. It is important to mention that this revenue should be

differentiated from the online 3D Models stock market. Although the 3D Models stock market provides 3D models, it offers a geometrical representation that is different from the Design Matrix defined earlier.

II. The Data-Operating Process Analysis

Figure 47 represents the data operation analysis for this case.

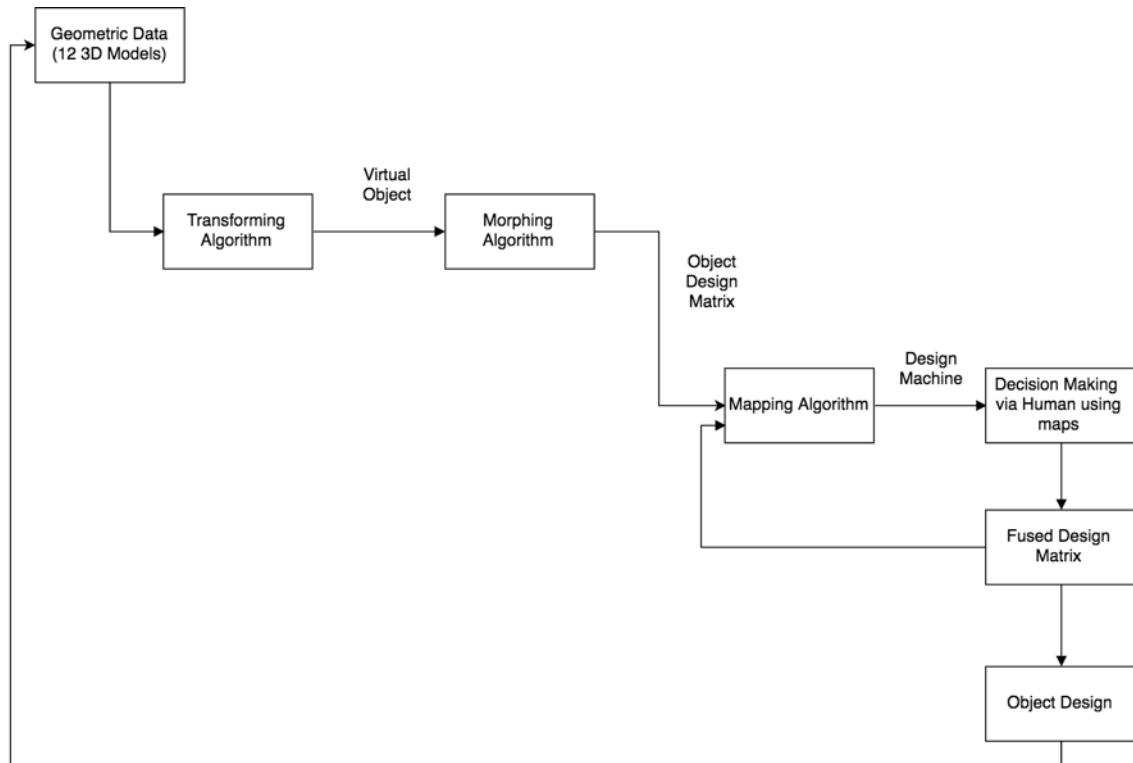


Figure 47. Four Chairs Case Study Data Process Analysis

III. Case Footnote

This case raises an ethical issue for the Intellectual Property of the original design. This Intellectual Property would be hard to identify and trace the original design. This is something that can be addressed and studied further.

Voxelisation[°] for generating 3D models is a potent modelling method which has been used in the gaming industry. The use of such a method has many benefits such as the reduction of the required computer power and enhancement of the capacity

[°] See Appendix 2: Terminologies for terminology

for design customisation (Eisemann & Décoret, 2006). An example of this is the game Minecraft. This modelling method is not used as much in digital design and exchange in architecture. Voxelisation may provide an opportunity to allow modelling to be crowdsourced, which might have useful applications.

In the Data Handling, a compressing algorithm was applied to compress the data; however, with the availability of *Big Data* software techniques, it is possible to skip this step and focus on enhancing the fusion of the design.

4.4.5. Human Behaviour and Spatial Configuration in Offices (Case Study 5)

This case proposes a data design approach that uses data about human behaviours and spatial configurations to inform the design decisions and particularly those related to workplace design. The case provides a method to allow an organisation to relocate based on insights generated from data.

This approach is based on simulation, and it is derived by analysing collected data, putting it into operation and then comparing the results as evidence. The case utilises a large amount of variable data but does not rely on *Big Data* techniques to achieve the objective. This data-driven design approach was achieved by the Space Syntax Laboratory and Spacelab Consultancy.

I. The Open Coding

a. Data Sources

There are five types and sources of data used in this case. The first is the main organisation's management; this data is collected by conducting structured one-to-one interviews with the principals. This data is used to create a deep, well-versed brief for the new location's requirements. The second is an online staff survey to investigate the individual needs in the workplace. The third is an observational study of the occupancy and occupants' behaviours, such as movements and interactions within the space. This observational study included modelling existing and desired collaboration patterns between the different departments in the organisation. The fourth is the use of a CAD Drawing (plan) to perform a spatial analysis of the current space. The fifth is data gathered from other organisations to set a benchmark and a comparison baseline.

In this case, the sources of data are Internal except for the last one, which is External. The first is a Design Brief created from interviews, the second is generated Internally through a survey, the third is generated through observations, the fourth is geometric data analysis representing the space, while the fifth is gathered from external sources and other organisations. Data in this case is Semi-Structured but mostly considered as Fast Data.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 51 Open Codes of the Data Source of Case 5

Open Codes	Codes from Text	Axial Codes
Data Source	Occupant Survey Observations Study (2) Occupancy Study Movement Study Interaction Study Interviews (2)	Input / Collection Input / Collection Input / Collection Input / Collection Input / Collection Input
Data Offering	Measurable Benefits and Criteria (2) Systematic Brief (2) Reveals Interaction and Collaboration Network Informed Decisions	Output - Information Output Output - Interface Intervention

b. Data Handling

The first step in preparing data to evaluate the space performance is to conduct a space-syntax analysis on the existing space using the CAD drawing in a software package. The space-syntax analysis focuses on the social and spatial dimensions of the space. The data is utilised to generate a Spatial Strategy for the organisation through a depth map software package. The software used is depthmapX. It is a “multi-platform software to perform a set of spatial network analyses designed to understand social processes within the built environment” (Varoudis, 2012). The software generates a depth map of the analysed space (Figure 48). The gradation of colours in these maps reflects the integration and segregation of open spaces. The analysis aims to extract variables that have social or experiential significance on the

relationship between the connected elements in an open space. This analysis works on a variety of scales from buildings to urban context.

The data is acquired and processed in batches. The analysis is descriptive, and there is no generating of simulations for future scenarios. Finally, the data generated from the analysis is compared to the benchmark data to assess the performance of the analysed space.

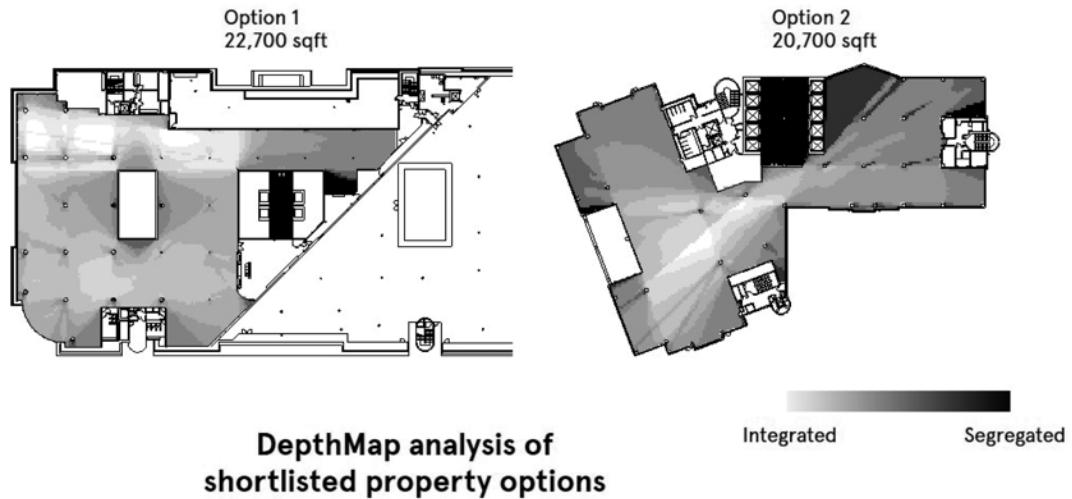


Figure 48 Depth Map Analysis for Two Properties Focusing on The Level of Integration and Segregation in The Spaces (Sailer, Pomeroy and Haslem, 2015)

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 52 Open Codes of the Data Handling of Case 5

Open Codes	Codes from Text	Axial Codes
Data Handling	Establish an Understanding Structured Interview and Surveys (2) Spatial Analysis (DepthMap) Data Layering Communication Gathering and Collection (3) Analysis (2) Modelling	Processing Collection Analytics / Modelling Analytics Modelling Gathering Analytics Modelling

c. Data Offering

The primary data offering that this case achieved is the generation of a new type of data. The Spatial Strategy was generated through the use of Data methods within the organisation. Sailer, Pomeroy and Haslem (2015, p. 253) defined the Spatial

Strategy as: “A master plan which maps key spatial relationships between the organisation departments, and the schedule of total recommended space requirements.”. The Spatial Strategy is supported by a depth map and comparative analysis. The depth map is a visualisation technique that relies on representing the analysed space with colour gradation to communicate the level of integration.

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 33 The Open Codes of the Data Offering of Case 5

Open Codes	Codes from Text	Axial Codes
Data Offering	Measurable Benefits and Criteria (2) Systematic Brief (2) Reveals Interaction and Collaboration Network Informed Decisions	Output - Information Output Output - Interface Intervention

d. Architectural Value Propositions

The Spatial Strategy can be used for two different purposes, the first is to inform the relocating decision for a potential future property, and the second is to develop and refine the existing space design to enhance the work environment (Sailer, Pomeroy and Haslem. 2015). The Spatial Strategy gives information related to space capacity, space furniture, space arrangement and space allocation. These are related to the Use value of the building. Spatial Strategies could be applied to different buildings to achieve various levels of space integration to enhance the use of space and the design efficiency. In addition, the space analysis provides information about the space’s potential to integrate or segregate occupants, which affects their interaction and satisfaction, which affects the Social and Psychological value.

The implementation of the Spatial Strategy has two advantages. The first is allowing the organisation to define the essentials Use values of the space design; these values are tailored to the specific needs of the organisation. The second is allowing the organisation to implement and measure a change in the space layout, and, finally, increase the sociability, productivity, happiness and well-being of its employees.

This approach has an effect on the Social and Use value of the built environment. The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 34 The Open Codes of the Value Propositions of Case 5

Open Codes	Codes from Text	Axial Codes
Value Proposition	Generate New Designs Compare Designs Inform Future Designs Enhance Space Long Term Value	Output / Intervention - Automated / Modelling Intervention - CAE Intervention - CAE Intervention - CAE

e. Digital Value Equaliser

Figure 49 represents the Digital Value Equaliser for this case.

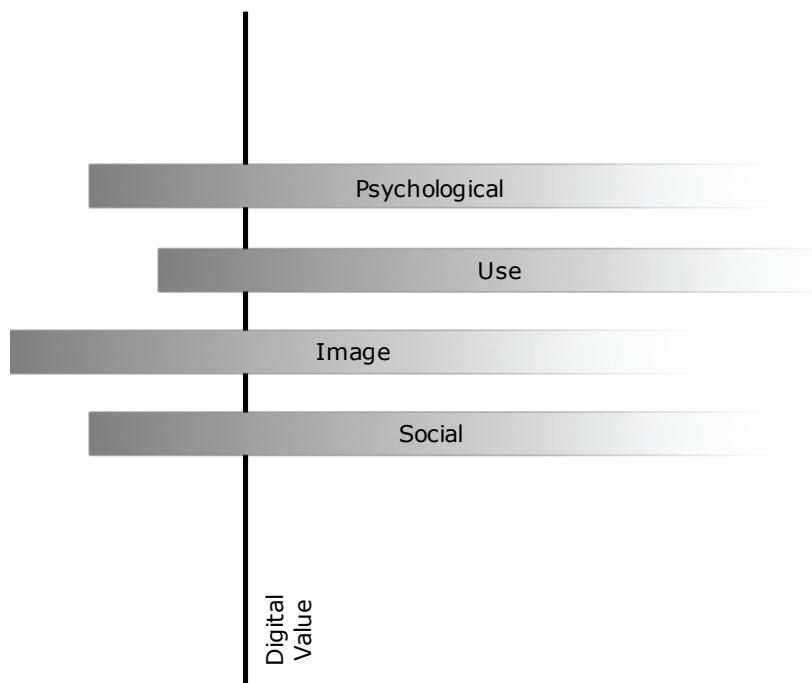


Figure 49 Case Study 5 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 35 The Data Codes of the Architectural Value of Case 5

Open Codes	Codes from Text	Axial Codes
Value	Use	Intervention - human Intervention - human Output Application

	Social	Potential of Space Integration or Segregation (2)	Output
	Image	Organisation Image	Output
	Psychological	Occupant Satisfaction (2) Occupant Happiness Occupant Wellbeing	Output

f. Architectural Business Channels

The Spatial Strategy discussed in this case is based on analogue data collected. It is possible that the data is adequate, and that it reflects the actual use pattern of occupants and respectively meets the organisation's needs. However, human intervention requires a great amount of time that can be automated using sensors and trackers. These devices will not interfere with the organisation's existing workflow. Using sensors at an early stage of this data implementation leads to establishing a comparison of the space's performance before and after the design adjustments or reallocation. Also, the same could be applied to pre-occupancy and post-occupancy situations. The method provides deeper design insights and proposes a real-time design tool.

The method of implementing data can be used with other types of spatial analysis in addition to the mentioned Space Syntax. These analyses allow different kinds of values to be achieved in the design.

Architects could build their business and design operations on the production of Spatial Strategies that provide design evidence and the opportunity for the buildings to have a continuous maintenance contract.

II. The Data-Operating Process Analysis

The following diagram represents this case analysis (Figure 50).

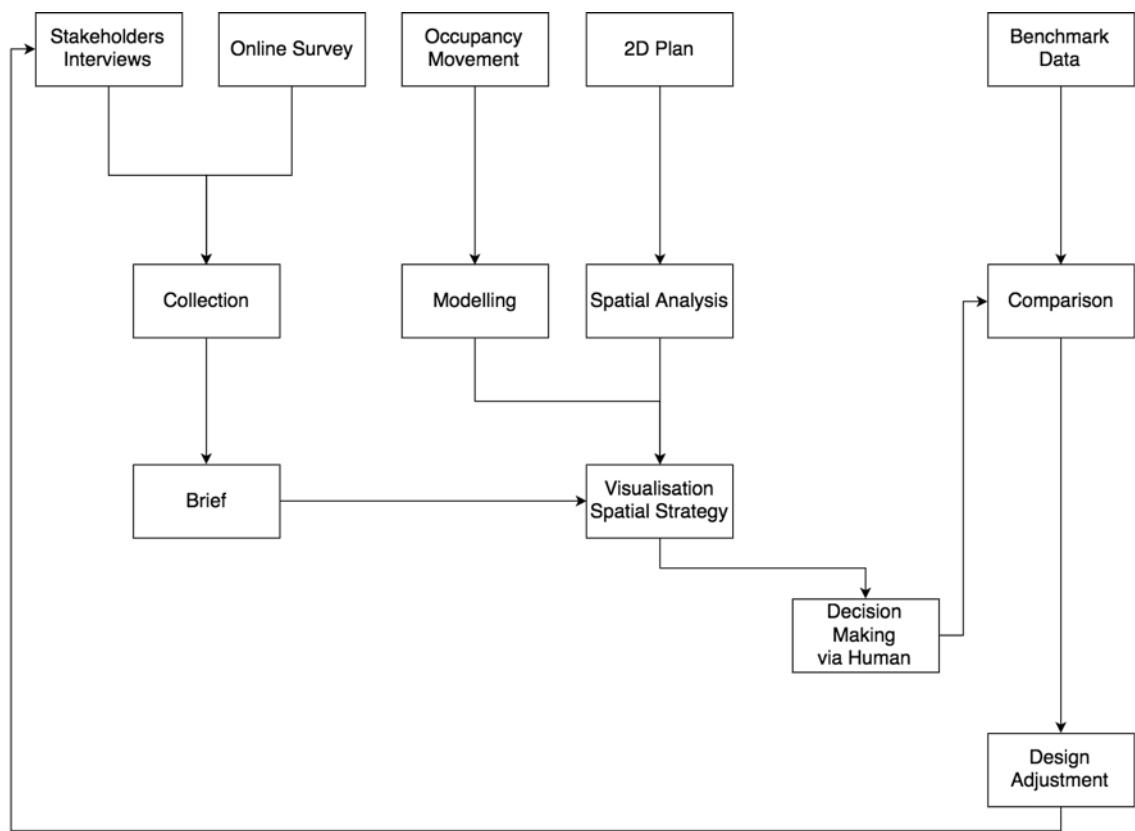


Figure 50 Human Behaviour and Spatial Configuration in Offices Case Analysis

III. Case Footnote

- There is a demand for an approach that addresses a client's specific needs by providing a tailored design that fits the client's requirements and ambitions.
- Benchmark Data is a term used in business. It refers to a resulting performance of a sector in relation to pre-defined parameters. Similar information is needed regarding spaces in the built environment. This information should provide data about how a space performs and how this is achieved. The availability of this type of information for different architectural projects allows a baseline for value comparison, enhancement and implementation.

4.4.6. Reveal It, My Position (Case Study 6)

This case focuses on the use of data provided by citizens to project information onto public displays and monuments, to inform and engage citizens. This approach to using data allows design applications that utilise social media and crowdsourcing platforms. There have been different attempts to use data to engage the public. Aether and Hemera (2013) created an interactive art installation, "Fluidity", which

aimed to express the complex dynamics of gender perception in space (Aether and Hemera, 2013). Another project is “CityBeat”, which is an academic study that seeks to use machine learning to provide insights about the city performance in real time (CityBeat, 2014). “Reveal it” was chosen for its different approach which provides both purposes: an interactive dynamic dashboard and a stimulus for behaviour change through increasing the awareness of energy consumption.

The case examines the potential of social visualisation in an urban environment context. The main objective of this case is to increase public social awareness and initiate public discussions by projecting profound analysis and exposing data patterns (Valkanova et al., 2013). The display presents data and information provided by citizens on an interactive screen. This interactive visualisation provides a comparison of the energy consumption of different individuals and communities. The tool is designed to support public exploration, reflection and debate on social issues.

The urban visualisation display was designed following the Design Space Explorer Framework for Media facades.

I. The Open Coding

a. *Data Sources*

The case data is provided by the public (Crowdsourced) through voluntary input using a web-based social platform. This web platform has a Form Interface that can be accessed individually through any tablet or smartphone. Participants provide information about their monthly energy expenses, their neighbourhood and the number of cohabitants in the household. This information allows the estimation of value consumption per household member. Each data entry is private and confidential, as the names are hidden when the information is projected onto the screen. The data sources are external, provided by the public and are considered Fast Data.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 56 Open Codes of the Data Source of Case 6

Open Codes	Codes from Text	Axial Codes
Data Source	Data sets of energy consumption Crowd-Sourced Data through Mobile Interface (2)	Input - Stored Input – Real Time Application - Interface

b. Data Handling

The data was generated by the users of the public space and collected in real time. The collected data was directly modelled into Visualisation. There is great emphasis on the Visual Mapping technique because it contributes to engaging and attracting more people to the installation. The visualisations, in this case, are Social Visualisations. Donath, Karahalios and Viegas (1999, p. 1) defined Social Visualisation as “The visualisation of social information for social purposes”. This visualisation employed subjective data that was based on public participation. The visualisation consisted of Sunburst Representation and dynamic visual elements (Figure 51).

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 57 Open Codes of the Data Handling of Case 6

Open Codes	Codes from Text	Axial Codes
Data Handling	Use Design Framework Data Entry Estimation Transformation	Input – Stored Input Analytics Modelling

c. Data Offering

The visualisation's main objective is to provide energy consumption data. The interesting visualisation attracts people and allows them to interact with the display. The raw data provided through the visualisation allows viewers to interpret the information individually. This individual exploration allows reflection on personal energy use and enlightens the viewers about their and others' energy-use patterns. Also, the display allowed collective social exploration which initiated playful

competition in some cases. People's reaction towards the display starts a social activity and increases awareness of the presented topic and the public space itself.



Figure 51 Screenshots of The Visualisation Interface (Valkanova et al., 2015)

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes of the case.

Table 58 The Open Codes of the Data Offering of Case 6

Open Codes	Codes from Text	Axial Codes
Data Offering	Exposing Underlying Patterns Insights about human response Insights about human perception Insights about Human Interaction Representation (2) Dynamic Visualisation	Output / Analytics Output/ Analytics Output / Analytics Output / Analytics / Intervention Modelling Modelling / Interface

d. Architectural Value Proposition

The case study shows that data-driven information in public visualisation motivates social communication and enhances the psychological experience. This experience motivates individual and public reflection on a space and initiates a collective discussion on the represented topic. The employed method communicates uninteresting facts related to energy in a playful, interactive public display. This approach allows a wider distribution of information and turns public visualisations into an urban communication and engagement tool.

In addition, the information conveyed through these Public Visualisations increase the public's awareness about the effect of their energy use on the economic and environmental aspects of the city (Valkanova et al., 2015).

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 39 The Open Codes of the Value Propositions of Case 6

Open Codes	Codes from Text	Axial Codes
Value Proposition	Public Interactive Projection Social Electronic Communication Playful Data	Application – Interface

e. Digital Value Equaliser

Figure 52 represents the Digital Value Equaliser for this case.

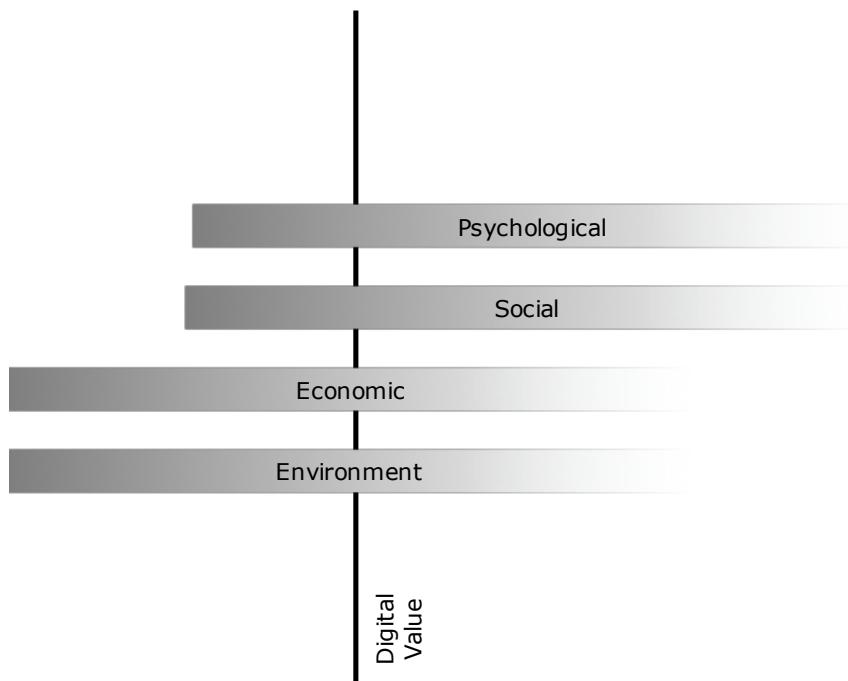


Figure 52 Case Study 6 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 40 The Open Codes of the Architectural Value of Case 6

Open Codes	Codes from Text		Axial Codes
Value	Social	Increase Social Awareness Increase Understanding Shared Understanding Supports Interaction Encourage Gatherings	Output / Intervention

	Economic	Enhance Energy Consumption (2) Reduce Energy Consumption	Output / Intervention
	Psychological	Public Engagement (2) Promote Curiosity	Intervention

f. Architectural Business Channels

Architects could start thinking of Public Visualisations and facades as an essential element of information and data communication. This method does not imply the use of public displays and facades as a means of advertisement but rather the use of them as an interactive and informative public design element.

In this case, the main contribution of data to the AEC industry is through implementing Spatialisation as a design element. Spatialisation as a general term means “the use of spatial metaphors to make sense of an abstract concept” (Skupin and Fabrikant, 2007, p. 2). In architecture, Spatialisation can be defined as transforming high dimensions of datasets into lower-dimensions of spatial representations that allow exploration and knowledge discovery (Skupin and Fabrikant, 2007).

The information provided by the public can be utilised in two ways. The first way is by displaying it in order to engage more people. The second way is by collecting it for further analysis and insights.

The possibility of expanding the design beyond the physical entity of the constructional elements by providing interactive displays is a channel of added services that architects and designers can focus on implementing. This channel works ideally in public spaces but can expand to include every type of space. This channel contributes to behaviour changes and has the potential to increase the sense of place perceived by the public.

II. The Data-Operating Process Analysis

Figure 53 shows the case analysis.

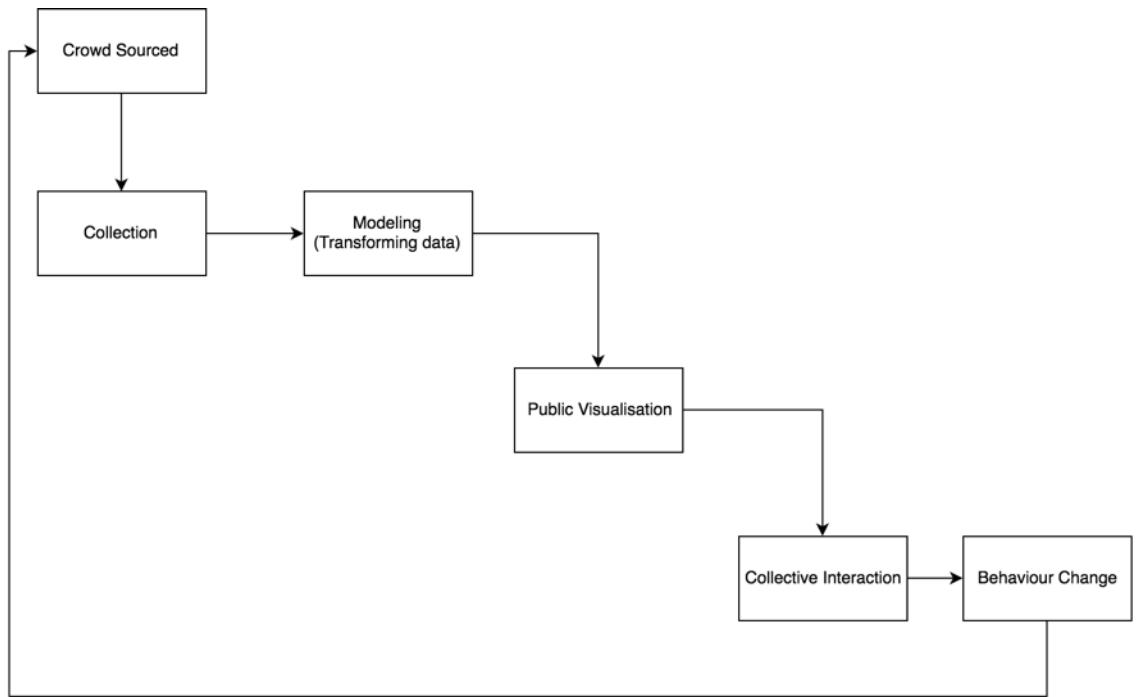


Figure 53 Reveal-It Case Study Analysis

III. Case Footnote

This case has some similarities and connections to the Liverpool ONE case study (Case Study 1) and the Chicago Energy Map case study (Case Study 2). The similarity with Case Study 1 comes from the data source, which is provided by the public. However, Case Study 1 does not allow people to enter their data or directly interact with the sensors. The connection with Case Study 2 is the fact that both cases aim to raise awareness of energy consumption, although using different methods and output techniques. These connections and similarities have the potential to be integrated together and provide greater offering and value.

4.4.7. SIG 04 (Case Study 7)

This case resembles architecture as a machine, a system that extends beyond a physical response to having a full empathetic, kinetic system, through which human activities are understood. The method, in this case, is described as “Sensponsive”, where Ambient Intelligent technology provides the space with cognitive skills and provides a sense of reasoning to adjusting its properties according to a user’s movements, needs and situation. This project was carried out by Oungrinis and Liapi (2014) at the Transformable Intelligent Environments Laboratory in the School of Architectural Engineering at the Technical University of Crete in Greece.

The case focuses on implementing this Sesponsive technology in a classroom environment to impact the learning experience positively by increasing the effectiveness and efficiency of the space's properties. This process uses machine learning to optimise the performance of a space based on the user's activity. The same framework is being employed in an intelligent spacecraft (Oungrinis et al., 2013; Oungrinis et al., 2014). This use of the framework shows the potential it has in various design environments of different contexts and purposes.

The system is based on four main components: Activity Evaluation System (AES), Dynamic Building Program (DBP), Responsive System (RS) and Formation and Reconfiguration (FandR). Figure 54 shows a diagram of the Sesponsive System. The AES is responsible for identifying the type of activity hosted in the space. The DBP is a real-time diagrammatic system that monitors the AES and responds to the change of activity with the objective of achieving optimum space utilisation. The RS acts as an interface for users and feeds into the DBP. The RS allows the space to change based on two modes of operation: interactive, controlled by the user through kinetic space elements, and automatic, controlled by a machine through an evaluation process. The FandR are the actual physical architectural elements that are reformed and designed based on the DBP signals (Oungrinis et al., 2013). The structure consists of three main elements: floor platform, ceiling infrastructure and flexible sidewalls. The analysis focuses on the whole system.

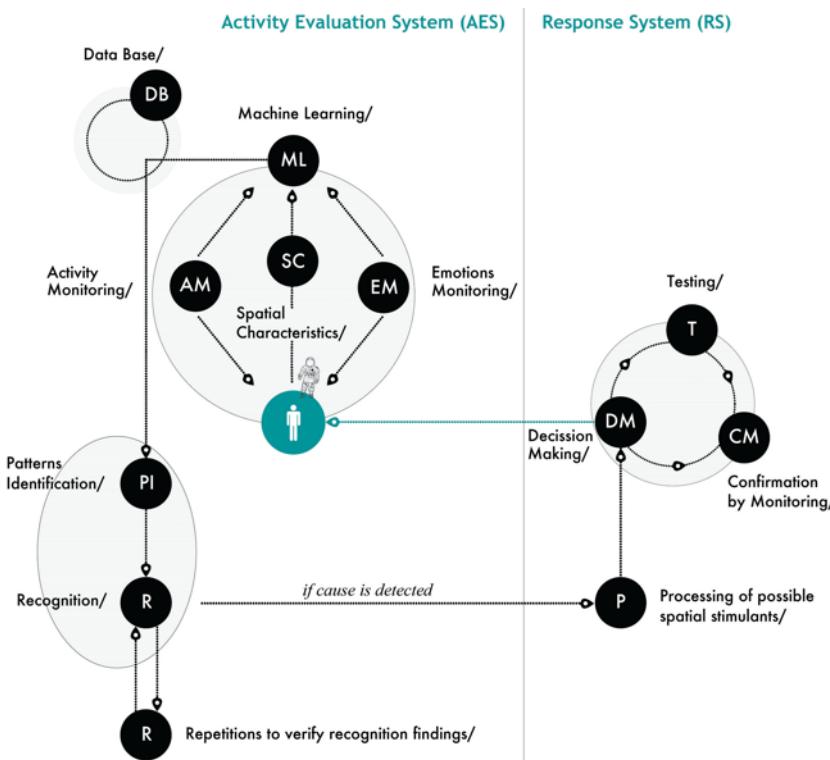


Figure 54 Diagram of the Sesponsive System (Oungriniw et al., 2014)

I. The Open Coding

a. Data Sources

Two sources of data are involved in this process: collected and generated data. The collected data is specific design parameters and characteristics that are inputted into the system and chosen from reviewing other research and studies of classroom designs to achieve a better learning environment. These parameters are Geometry, Light, Acoustics and Ventilation. These parameters address five unique scenarios and modes of teaching; these modes are Lecture, Discussion, Presentation, Board and Debate. The collected data represents the primary database in which the system is operating. The collected data aims to set optimum performance and scenarios based on external studies. Figure 52 shows the modes and associated parameters.

The generated data is gathered during the occupation of the space. This data is generated according to the human activity, the occupation situation and the interaction with the Sesponsive system. The generated data aims to optimise the system, to refine its behaviours and to allow a customised experience for the space user. The generated data is stored back in the database of the system as a reference for continuous machine learning.

The data used is External, which is selected by designers, and Internal, which is generated from user interactions. The data in this case is a combination of Fast Data and Dark Data that has Automation and Actionable characteristics.

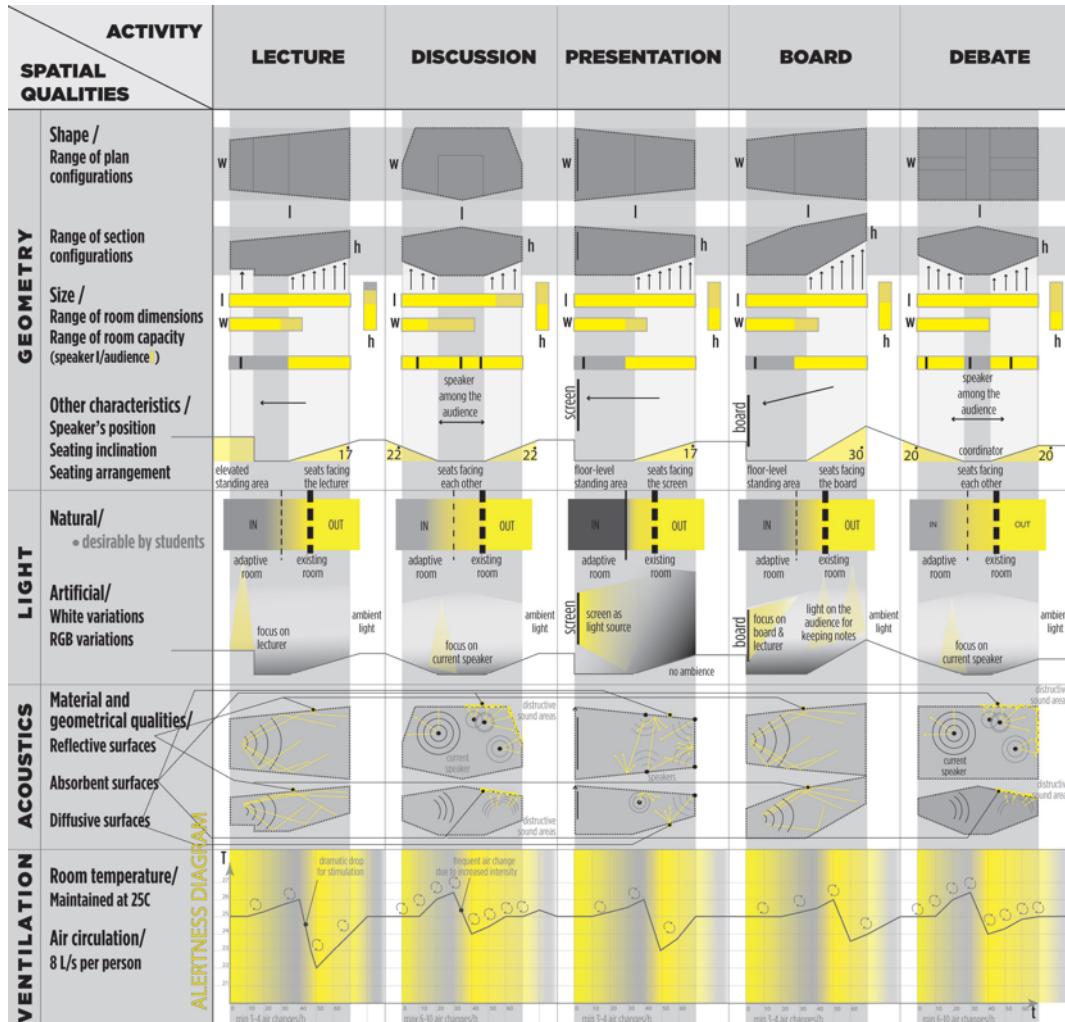


Figure 55 The Classroom's Responsive Parameters (Oungrinis Et Al., 2014).

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 41 Open Codes of the Data Source of Case 7

Open Codes	Codes from text	Axial Codes
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Data Source	Human Activity Observation Environmental Data Sources Activity Evaluation System Dynamic Building Program Responsive System Sensponsive System Parameters	Input – Real Time / Intervention Input – Stored Input – Real Time / Intervention Analytics Analytics Input
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b. Data Handling

Data is collected regarding the suitable and appropriate parameters that affect the classroom design, specifications and structure. This data forms the primary database, on which the machine-learning system is operating. The machine learning is linked to identical virtual and physical models that are designed to enable the virtual adaptation of the five modes through the applied “Sesponsive” framework. The physical model is a 3D printed version of the virtual model. The machine learning has algorithms that adjust the ambient and spatial characteristics with regard to the chosen mode of operation. A human decision to override the selected parameters causes the system to look for a spatial stimulus that is associated with the override. The system recognises this change and links the stimulus to the recorded event. The recorded events are analysed to identify unique performance patterns, then the system registers the recorded event as an activity in the database. This process of handling data is continuous.

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 42 Open Codes of the Data Handling of Case 7

Open Codes	Codes from text		Axial Codes
Data Handling	Adopt Ambient Intelligence Framework Identify Compute Orchestrate Collect Relate (2) Assess Direct Change Monitor Assembling Pattern	Time Understanding Intention	Input Collection / Aggregation Processing Analytics Collection Processing Recognition Processing Modelling Collection / Aggregation Analytics

c. Data Offering

The data enables an automatic adjustment of the built environment based on the simulation of occupant's activity. This approach provides a user-centred automatic space reconfiguration. This reconfiguration is taking place and affecting real-life smart materials and elements that are capable of adjusting the geometric configuration, light, and acoustic and ventilation properties of the space.

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes.

Table 43 The Open Codes of the Data Offering of Case 7

Open Codes	Codes from text	Axial Codes
Data Offering	Space Response Human-Centred Design	Intervention - Automated

d. Architectural Value Proposition

In this case, the Data Offering allows a direct Value Proposition – a designed space with responsive spatial characteristics, a fully operational imbued space which has an 'augmented value' environment for occupants.

The first observed value is the contribution of the space to the activity outcomes by adjusting the spatial qualities to optimise the ongoing activity and boost the required conditions, such as productivity. The second is allowing more discussion and social activities to take place between people in the space by providing optimum social conditions. However, the Data-Driven implementation has two other potential values: the first is saving energy due to the change of spatial qualities according to the teaching activity, and this also means the possibility of shutting down when the space is not occupied. The second is engaging students by allowing the space to work as a learning stimulator.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 44 The Open Codes of the Value Propositions of Case 7

Open Codes	Codes from text	Axial Codes
Value Proposition	Space Reconfiguration Scenario Design	Intervention – Automated

	Smart Materials (Electroactive and Electrorestrictive Polymers)	Output / Intervention – Human Application – Smart Materials
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e. Digital Value Equaliser

Figure 56 represents the Digital Value Equaliser for this case.

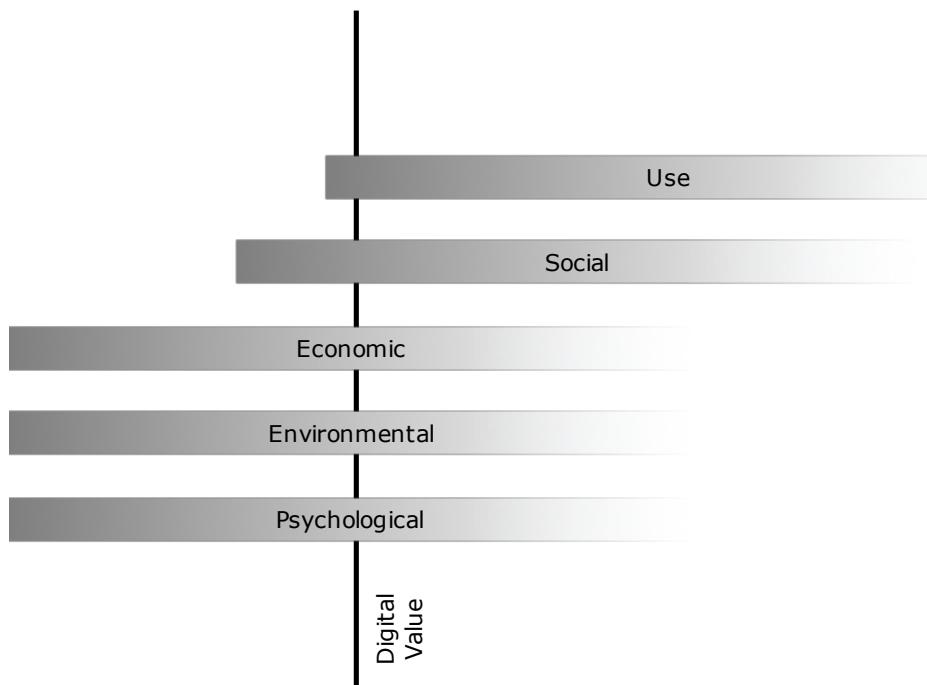


Figure 56 Case Study 7 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 45 The Open Codes of the Architectural Value of Case 7

Open Codes	Codes from text		Axial Codes
Value	Use	Empathic Space Spatial Response in Time	Intervention – Automated
	Social	Discreet Response Influence Health Influence Behaviour Influence Performance	Intervention- Automated Output / Intervention - Human
	Economic	Automatic Space	Intervention - Automated
	Environmental	Environmental Adaptation	Intervention - Human
	Psychological	Influence Emotions	Intervention - human

f. Architectural Business Channels

One value channel that architects should consider is designing the space not as a fixed design but as a changeable and responsive space which allows certain reconfigurations to take place and the space to change according to user needs and occupancy. The space's features and changeability could be an added value to the design contract. This channel could benefit from the use of other peripherals and smart device technologies. The consideration of responsive spaces as part of the design would allow the design of whole responsive buildings that respond to changes in the performance of urban spaces.

II. The Data-Operating Process Analysis

Figure 57 represents the analysis for the case.

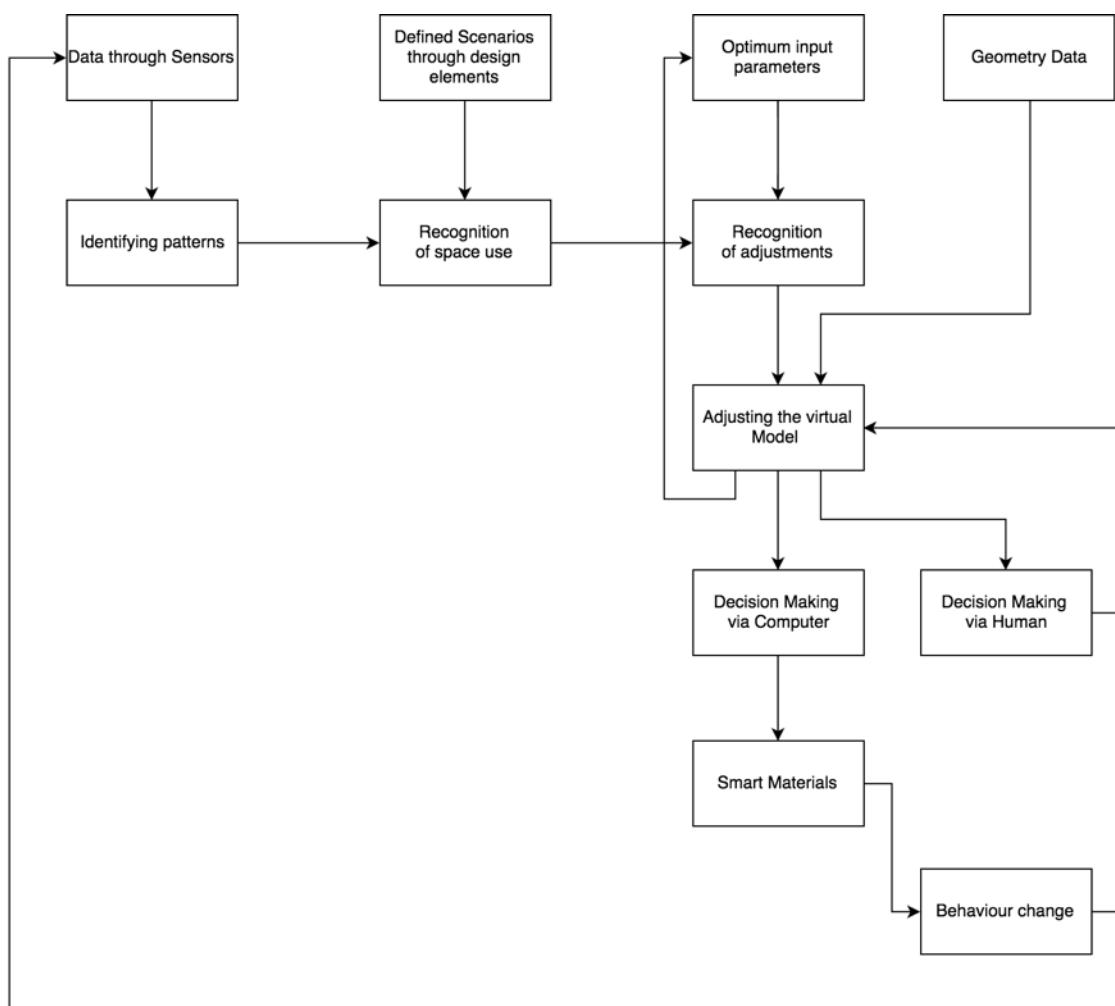


Figure 57 Sig 04 Case Study Analysis

III. Case Footnote

- This case focuses on the data during the operational mode, which is the data collected from users using the implemented sensors. This data can be enhanced by implementing other sources such as the data generated from the ubiquitous smart devices (the *Internet of Things* devices).
- This method of implementing data in design is restricted to the availability and advancement of the technology. This is considered a new progressive design approach of design.

4.4.8. Hospital Project Using RFID and BIM (Case Study 8)

This case utilises data in the operational stage of the construction process (Costin, Teizer and Schoner, 2015). This case is significant because of the application and use of the BIM platform as part of the data implementation process. The case employs a real-time tracking system for materials, equipment and personnel on construction sites, to improve the following: security, safety, quality control, worker logistics and scheduling of the construction process. The method combines the application of Building Information Modelling (BIM) and Radio Frequency Identification (RFID) technologies.

This case exemplifies all the cases that use different short-wave frequency technologies to achieve the same objective, including the use of RFID, Ultra-wideband (UWB[°]), A wireless local area network (WLAN) and other Telematics[°] technology. These technologies have been used successfully in many applications in the built environment including on-site real-time tracking, inventory and assets management, and security enhancements (Costin, Teizer and Schoner, 2015). Also, the case exemplifies the projects that use long communication technologies such as Telematics. Telematics has been used to monitor construction vehicles on job sites. For example, Nick Savko and Sons used Telematics in the CSX Railroad trans-shipping terminal project (Sprouls, 2010).

[°] See Appendix 2: Terminologies for terminology

RFID is a technology that uses radio wave communications to send messages. The technology is composed of a readable RFID tag and a RFID reader. The RFID tag is placed in inventories or a card. Each tag has stored information and data that is unique. The RFID reader transposes the radio signal to the tag wirelessly and then receives it back as information, which is transmitted to a processor for analysis or storing. In this project, 80 RFID readers were installed at various locations in different zones of the infrastructure of a new building. Each zone had a reader placed at its access point. The RFID tag was given to each person involved on the work site.

I. The Open Coding

a. Data Sources

There are three types of data involved in this process: the BIM model, the data from the RFID readers, and the performance measures. The BIM model has the geometrical attributes of the construction site, and it is considered the base to host all the other types of data. The BIM model is an internal source of data. The RFID readers generate data that is compared to the performance measures to determine the performance of the construction site. The RFID data is considered Internal data. The last type of data is the performance measures, which are metrics obtained from an external source and considered Lost Data.

The following table shows the words extracted from the literature that represents the Data Source and the associated Axial Codes.

Table 46 Open Codes of the Data Source of Case 8

Open Codes	Codes from text	Axial Codes
Data Source	Building Information Modeling Cloud Server Location	Input – Stored Input – Real Time Input - Location

b. Data Handling

The data handling has three stages: Data Collection, Data Filtering and Applying Performance Measures. The real-time data that is generated through the system is collected and stored for further use. This generated data includes the location of

each RFID tag and the information planted in the tag. The planted information consists of the RFID badge number, Timestamp and the reader internet protocol (IP). The IP allows identification of the zone in which the tag is being scanned. The data is stored on a cloud-based server and is categorised based on its type. The Data filtering includes the use of algorithms to eliminate read anomalies, reduce redundant data and filter the data in multiple organisations to facilitate the application of performance measures and analysis. Metrics are used on the organised data to allow various measurements such as Work Time and Travel Time. These two metrics are used in determining Time Efficiency and Output Efficiency. The data analysis is automatic and can be visualised through an interface so that comparisons can be made.

This case utilises the BIM process and platform for the use of the RFID technology. The RFID tags and readers were implemented in the BIM intelligent model using the IFC[°] (Industry Foundation Classes) format. The RFID tags are classified as actors and modelled as IfcActor. The RFID readers are classified as building elements and modelled as IfcBuildingElement. Each RFID tag contains some information about the person holding it such as ID, Name and Trade.

The following table shows the words extracted from the literature that represents the Data Handling and the associated Axial Codes.

Table 47 Open Codes of the Data Handling of Case 8

Open Codes	Codes from text		Axial Codes
Data Handling	Integration (2) Simulation Modeling (2) Algorithm Filtering (2) Analysis (2) Aggregation (Data Reduction) Reasoning Evaluation Utilisation (2) Gathering Communication	Identify the needs Project definition Evaluation criteria Implementations Options Deployment process Measurement and Evaluation	Analytics Modelling / Future Modelling Analytics Aggregation Aggregation Aggregation Processing Processing - Analytics Gathering Modelling

[°] See Appendix 2: Terminologies for terminology

	Identification Generation		Processing Analytics
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c. Data Offering

The cloud-based platform allows real-time daily reporting through email notifications. The reports include visuals and images that provide further information. In addition to reports, the cloud has an external web service that is accessible by clients.

The connection of RFID tracking data and BIM allows the real-time monitoring of the flow of people inside the construction site. This data is instrumental in emergency or safety situations. The site manager can predefine the non-accessible zones in the project, and the system sends alert notifications when a breach is committed. The use of RFID can be applied to any other equipment and objects on the construction site.

The overall integration creates a systematic and automated method to monitor the work on the site. The use of this data improves safety and security, allows continuous tracking of resources, increases protection, improves quality and worker logistics on the site, and, finally, allows accurate records of work time and payments to be kept (Costin et al., 2015).

The following table shows the words extracted from the literature that represents the Data Offering and the associated Axial Codes of the case.

Table 48 The Open Codes of the Data Offering of Case 8

Open Codes	Codes from text	Axial Codes
Data Offering	Real-time tracking Statistical Data Asset Tracking Inventory Management Zone Occupancy Activity Analysis Number of Works Visualisations	Collection – Real-time Input – Stored Intervention – Automated Intervention – Human Output Analytics Output Application - Interface

d. Architectural Value Proposition

The use of tags makes it possible to assign information to any architectural elements and objects. The same approach operates with different technologies including Bluetooth and Wi-Fi. The tag provides extra information that is useful in real-time tracking and monitoring. This technology is used in the construction process to allow better management. However, it can also be utilised in the post-occupancy phase. An architectural-designed space with tagged architectural components provides a better understanding of the space use. Linking the BIM model with these technologies is one feasible way of extending the functionality of the BIM model.

In addition to the mentioned utilisation of the data, the efficient use of *Big Data* and the *Internet of Things* solutions to record the architectural settings and the human-space interaction provides an extensive database of human uses of various space iterations and settings. This database will allow the discovery of the correlation between users, space and architectural components. This correlation supports the decision making of future projects and design adjustments.

The following values are observed: first is increasing the management, productivity and profitability of the construction process, which allows better economic returns. Second is providing a more sustainable construction process in which materials and resources are tracked and monitored.

The following table shows the words extracted from the literature that represents the Value Propositions and the associated Axial Codes of this case.

Table 49 The Open Codes of the Value Propositions of Case 8

Open Codes	Codes from text	Axial Codes
Value Proposition	Event-Based Response Real-time Automated Job Site Real-Time Digital link between virtual model and Physical Components	Intervention - Real Time Intervention – Real Time – Human Intervention - Automated

e. Digital Value Equaliser

Figure 58 represent the Digital Value Equaliser for this case.

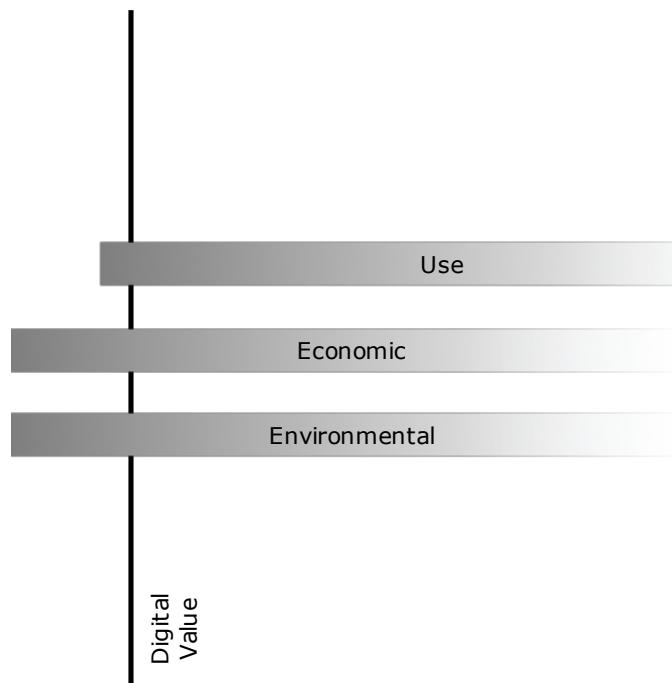


Figure 58 Case Study 8 Digital Value Equaliser

The following table shows the words extracted from the literature that represents the Value.

Table 50 The Open Codes of the Architectural Value of Case 8

Open Codes	Codes from text		Axial Codes
Value	Use	Easier Evacuation Safety and Security Control (2) Regulations (2) Efficient Planning Effective Workforce	Output / Intervention – Human Intervention – Human
	Social	Increase and Optimise Productivity (3)	Output / Intervention - Human
	Economic	Time Cost (3) Schedule Limit Damage Resources Tracking and Protection	Output / Intervention - Human
	Environmental	Optimise Material Use Quality (2) Impact	Output / Intervention - CAE

f. Architectural Business Channels

Costin, Teizer and Schoner (2015) stated that introducing automation through technology integration reduces the human component in the construction process and increases work accuracy, productivity and reliability.

Architects need to start thinking of spaces as smart structures and elements, even in design services. There are already home appliances that use Wi-Fi technologies and provide a different level of interaction between occupants and space. The *Internet of Things* makes it possible for every architectural component and piece of furniture to have intelligence and connectivity. There is a potential for integrating these technologies as part of the design and as an add-on service. Architects need to rethink Telematics and other Wi-Fi-enabled devices as part of the design contract where these devices can be used to connect architects with occupants and can be part of the business.

II. The Data-Operating Process Analysis

Figure 59 shows the data operation process analysis for this case.

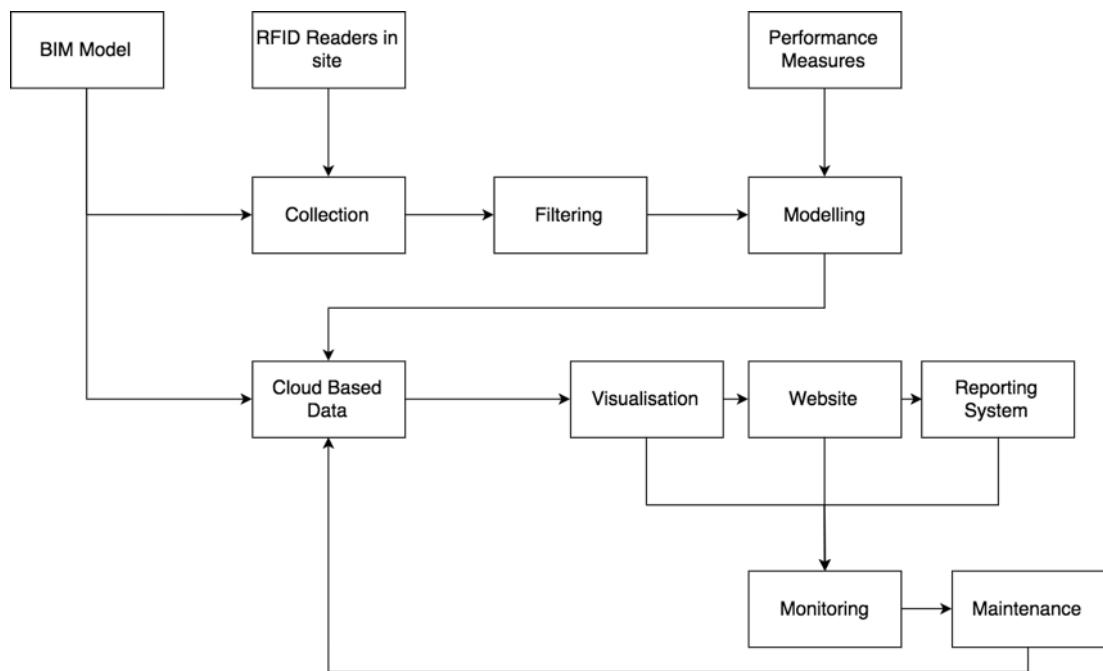


Figure 59 RFID-BIM Case Analysis Diagram.

III. Case Footnote

- The case had a deficiency in achieving full implementation due to the huge amount of data generated through the RFID readers; this data is hard to handle manually and causes data overloads. This suggests the need to implement a *Big Data* technology. Also, the suggested use of RFID

technologies does not allow the exact locating of the objects and personnel. That is due to the limitation of the RFID tags and readers.

- This case takes advantage of the BIM process in achieving wider data implementation. The author predicts that the BIM platform will provide a starting base for more data implementation in the design process.

4.5. Case Studies Value and Data Offering Summary

The following table summarises the case studies' data offerings, value propositions and the proposed architectural business channel.

Table 51 Case Studies Value and Data Offering Table

	Architectural Business Channel	Architectural Value Propositions	Data Offering
Case 1	Direct connection with users in space through mobile devices	Walkability Assessment	Visualisation
Case 3	Direct connection with occupants through a web application	Change individual and collective behaviours through visualisations	Visualisation
Case 3	Data Ecosystems	Integration of Dashboards and Computer-Aided Design tools	Information
Case 4	Web-based Object Design Matrix Libraries	Design Fusion	New Design
Case 5	Spatial Strategy	Decision support	Information
Case 6	Urban Façades and Public Visualisations	Enhance Users' Space Awareness	Visualisations
Case 7	Responsive Buildings	User-centric responsive space	Responsive Space
Case 8	Telematics and Wi-Fi as part of the contract	Architectural Tags	Report and Monitoring System

4.6. Case Studies Operating Process Analysis

As presented previously, each case study has a diagram as part of the case description and analysis that shows the Data-Operating Process Analysis. This diagram shows the Data Sources of each case and breaks down the data handling process into several components. The main aim of such a diagram is to identify the similarities and the connections between the several components in all the cases. Each component is represented by a rectangle, and the connections are represented in arrows that link these components. In order to draw such a diagram, a coding procedure following the Grounded Theory for the data-handling process of each case was completed. Each analysis is coded and the components involved in the process are analysed. After identifying the main data operational components and connections of each case, another coding procedure is completed for all cases together. This coding focuses on identifying categories for these components. This coding is represented in colours. Each colour reflects specific categories of the data operational process. Table 52 shows the colours that are used for the coding and the categories. The colour coding reflects the different phases of the data implementation. Figures 57 to 64 show the colour-coded Data Operation Processes for each case.

Table 52 Colour Coding of the Case Studies Data Operational Process Diagram

Green	Raw unprocessed data available in source
Yellow	Data processes within a computer
Red	Information through output platforms
Blue	Knowledge Discovery and Decision Making on Human Level
White	Reaction or output regarding the new decision

Case 1

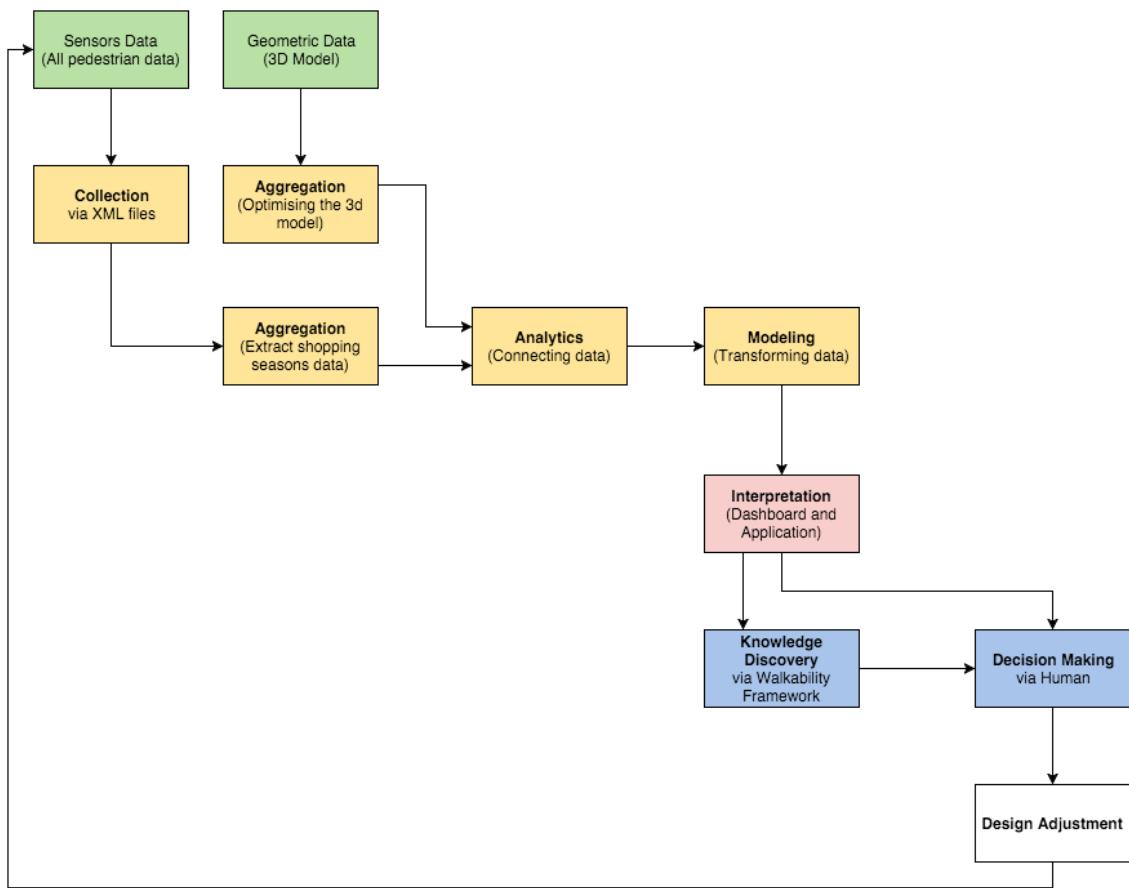


Figure 60 Case 1 Color-Coded Analysis

Case 2

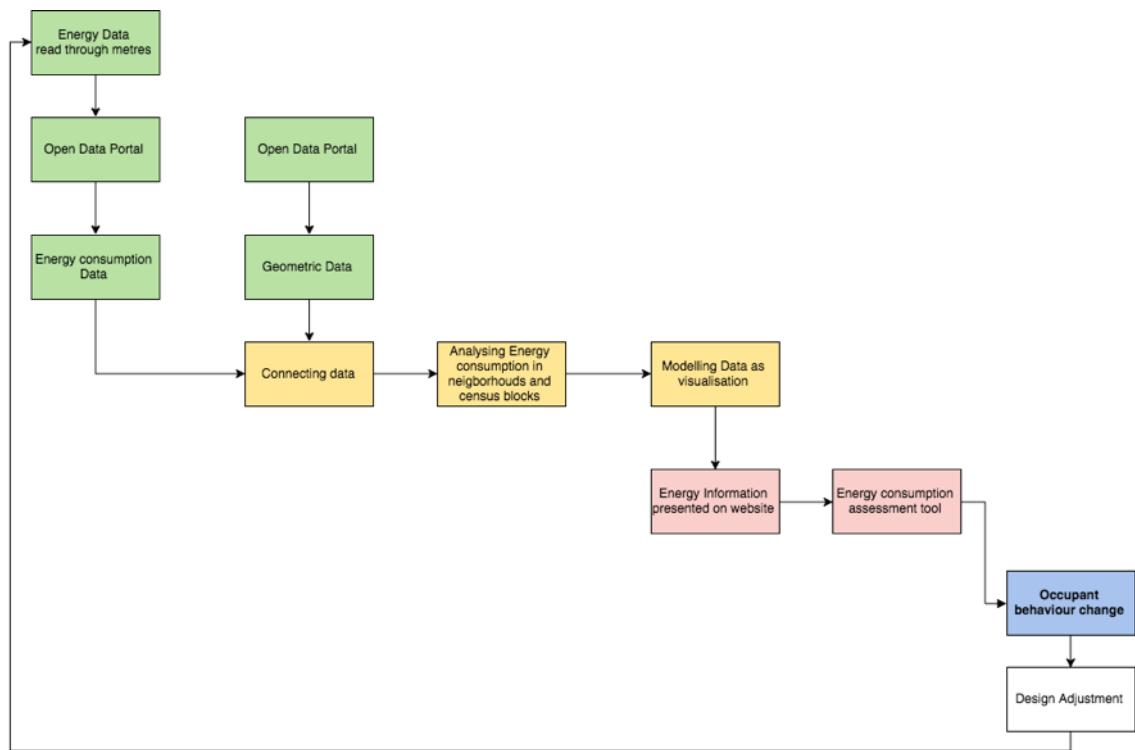


Figure 61 Case 2 Color-Coded Analysis

Case 3

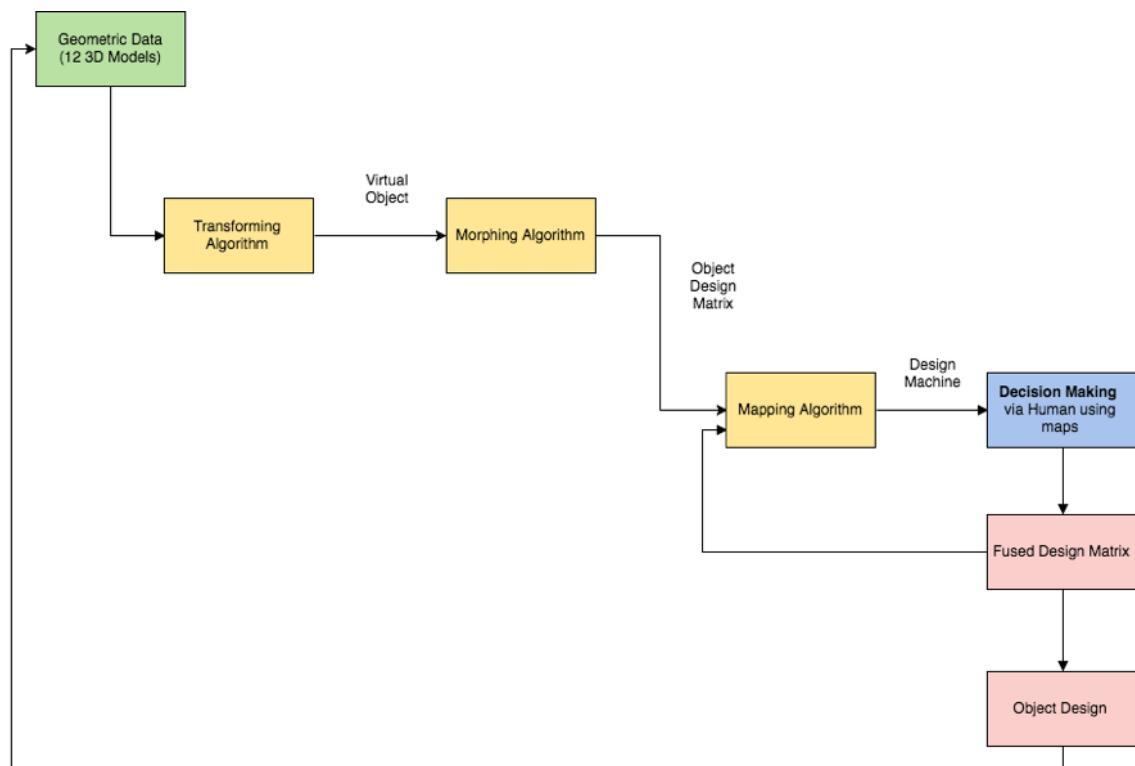


Figure 62 Case 3 Color-Coded Analysis

Case 4

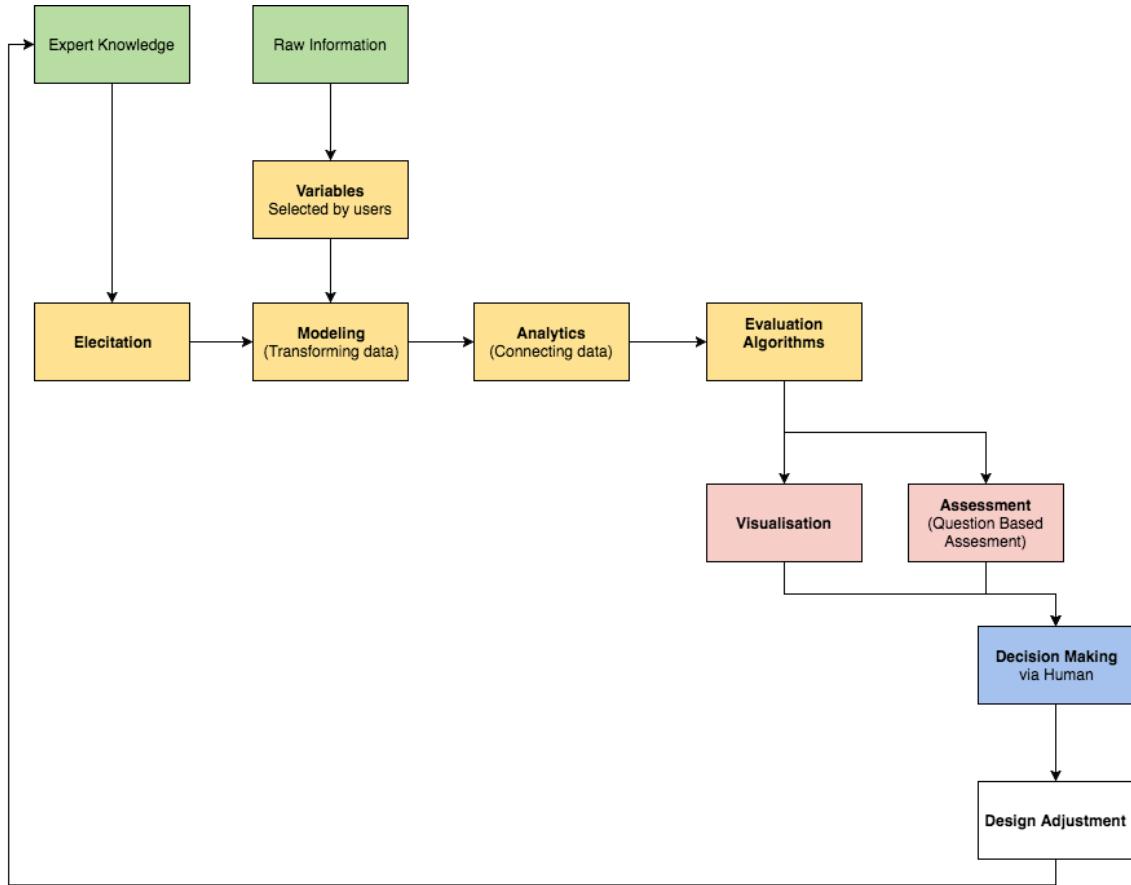


Figure 63 Case 4 Color-Coded Analysis

Case 5

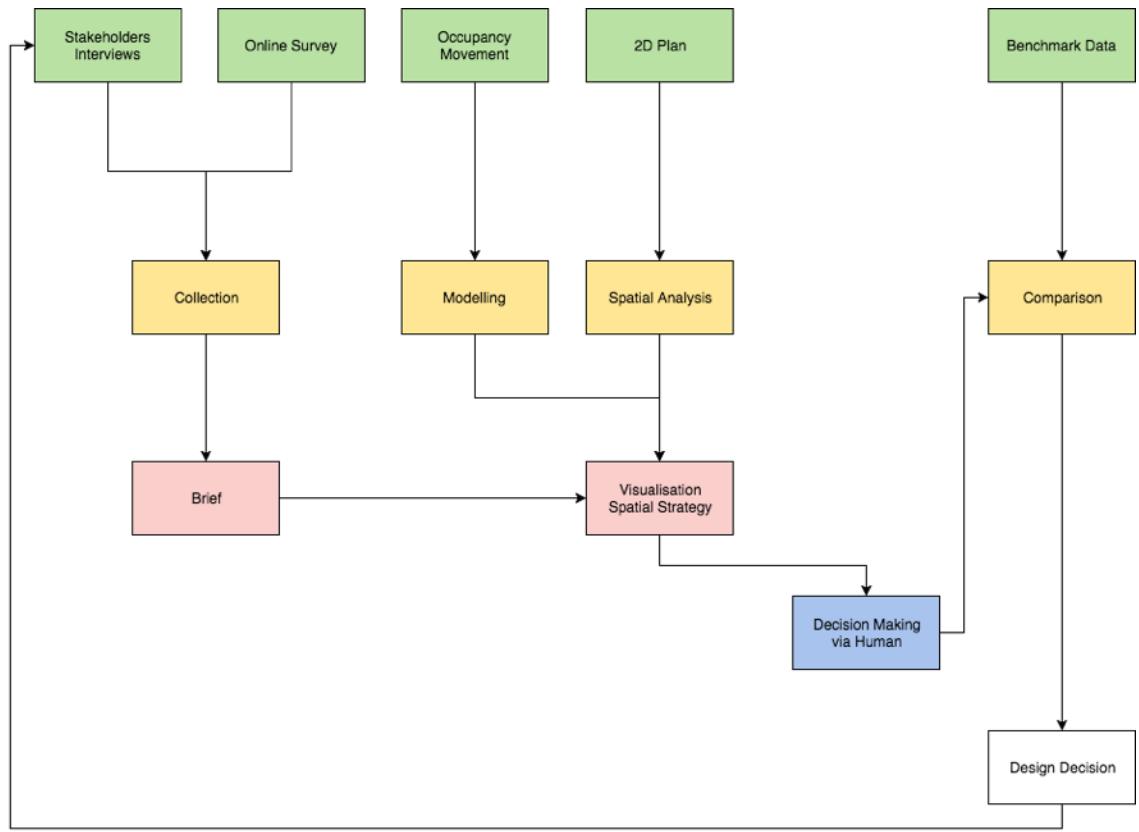


Figure 64 Case 5 Color-Coded Analysis

Case 6

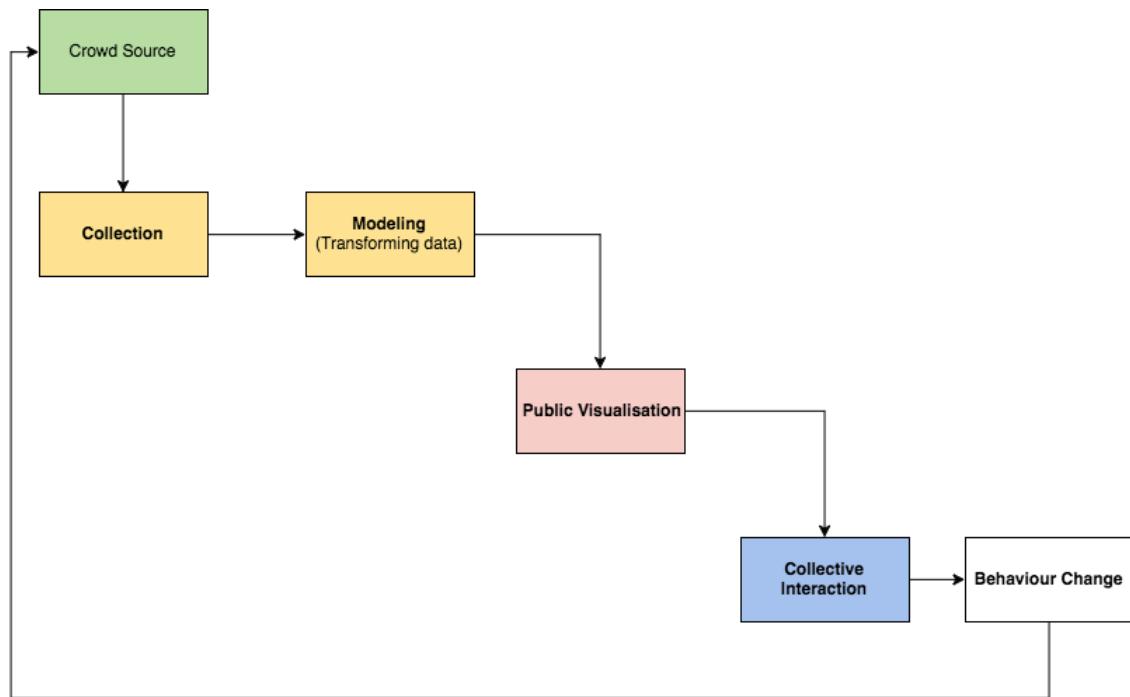


Figure 65 Case 6 Color-Coded Analysis

Case 7

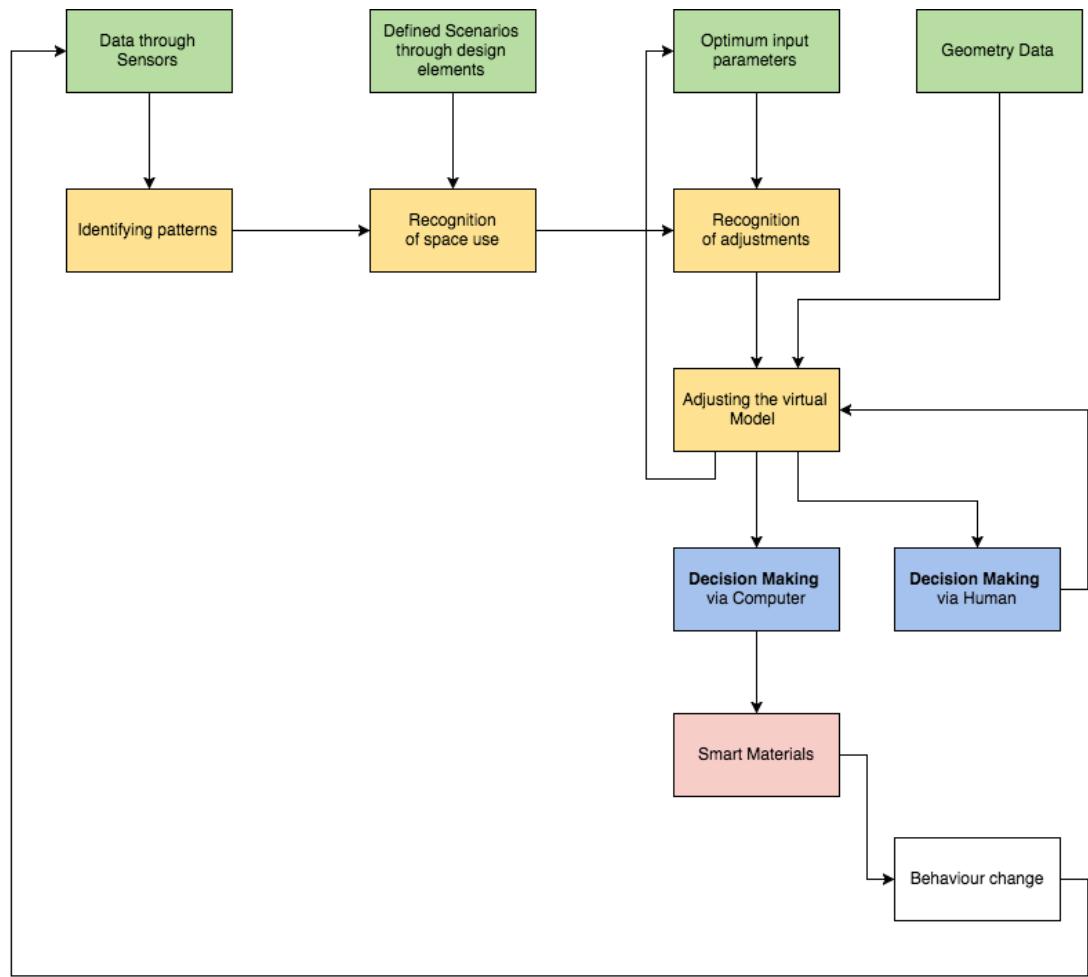


Figure 66 Case 7 Color-Coded Analysis

Case 8

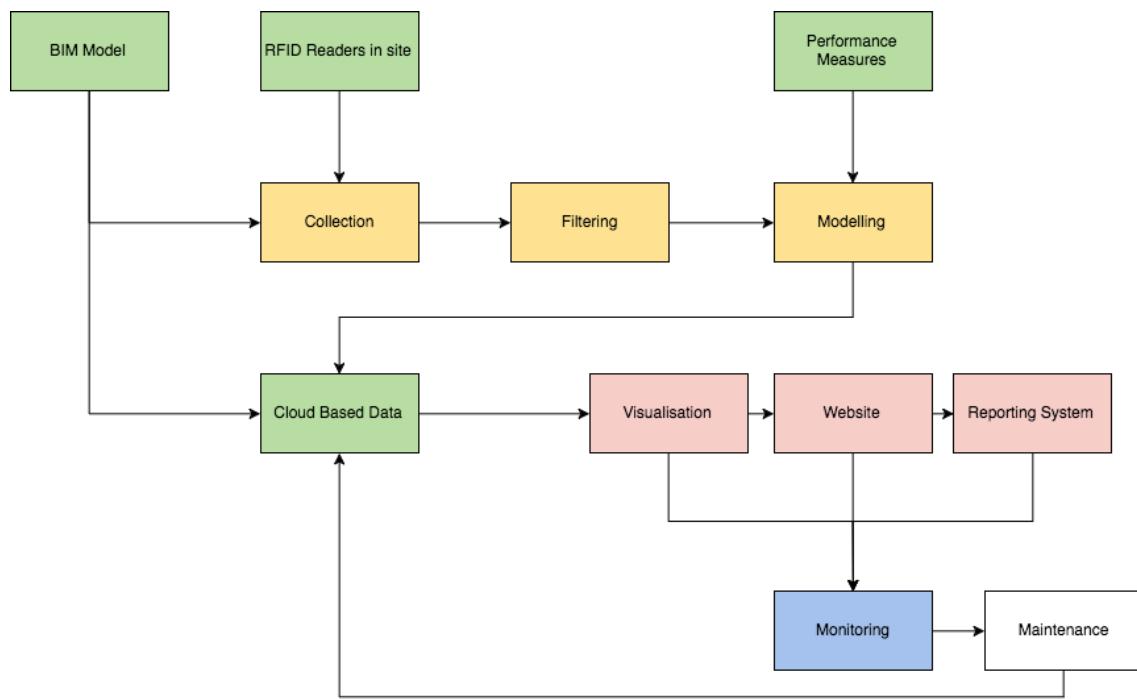


Figure 67 Case 8 Color-Coded Analysis

4.7. Analysis Matrix^{*}

The cases were analysed in a matrix to provide a flat representation of the analysis which allows a thorough understanding of the relationship between different components and how they contribute to achieving the allocated value. While the matrix does not highlight the important factors in the design process, it offers a base for comparison and indicates the most commonly used components in the data process.

Since each analysed case has been chosen to represent a unique method and to show one approach of using data, it is possible to identify some connections between the data-driven components.

Some correlations can be identified between particular types of data and their value impact in the data operation. As an example, to achieve a Social Value it is necessary to employ social data in the process. While this correlation seems obvious, the

^{*} See Appendix 3: The Case Studies Analysis Matrix

analysis allows a deeper understanding of the process of data acquisition, analytics and the type of offering.

4.8. Findings

- There are three identified themes for how a Data-Driven Operational Model could contribute to architecture. These themes are: Digital Enhanced Business, Proposed New Opportunities and Digital Integration.
- The implementation of GIS- and GIS-based services is more developed than any other location-based technologies in the built environment as realised in Case Study 3. This is due to the availability of open universal maps which provide easy access to designers, developers and programmers to implement the technology. The properties of GIS provide advantages for Urban-scale applications over indoor location application.
- BIM (Building Information Modelling) provides an excellent foundation to integrate more types of Data as realised in Case Study 8. This is due to the increased use of BIM and the realisation that the information in BIM is more important than the modelling technique. The BIM process has become flexible, and data add-ons have been enabled; this has initiated an approach by which to achieve Building Information Management.
- It is recommended to establish a smart grid or network for designers and architects that allows early data intervention based on design perspective and architectural value assessment. Smart buildings should be an extension of this grid and allow universal applications. The reason for this recommendation is to provide a unified data source for all data-driven approaches. All of the cases studies rely on a separated data source with no integrations and unity.
- It is recommended to establish an architectural design data infrastructure as part of a wider *Big Data* Ecosystem. The reason for this recommendation comes from the cases where each case utilises different types of data from external sources and generate architectural data internally. The data could be used from in other fields and for other uses
- There is a need for data de-aggregation or decomposing. A very critical process in utilising data is the ability to trace the origin of the data and how the current

information has been acquired. It would be useful for the data process to be able to obtain the original data and reuse it.

- The importance of setting up universal architectural metrics for each stage of the design in order to allow a universal assessment of the AEC process.
- In addition to having metrics for the development and build process, it is important to establish metrics for other aspects of the design such as the cultural value and the social value.
- The possibility of adjusting the current architectural Fee-For-Service based on the Added Value which can be monitored using the proposed value metrics.
- There is the potential to implement Telematics and tracking devices as part of the architecture and construction process.
- There is the potential to employ smart materials and automated architectural elements as part of the architectural contract. This would not have been possible without the *Big Data* and the *Internet of Things* technologies.
- There is a need for a new set of expertise and modern educational methods to train architects to enable them to contribute and take an efficient role in the digital design process.

4.9. Summary

This chapter has described the case studies and presented the information extracted from each based on the coding procedures that are associated with the Grounded Theory. However, the coding and analysis procedures have not been elaborated on in this chapter because this takes place in the following chapter (Chapter 5: The Development of the Data-Driven Operational Framework). The following chapter is dedicated to explaining the coding procedures and the interrelations between them, which provides a better understanding of the methodology and led to the establishment of the Data-Driven Operational Framework as an output of this analysis.

Chapter 5: The Development of the Data-Driven Operational Framework

This chapter builds on the analysis and knowledge obtained from the case studies. It aims to demonstrate the construction of the Data-Driven Operational Framework and the operational models associated with it. This is achieved through the various coding procedures. The coding led to the emergence of the core concepts of the data-driven operational levels and impact.

The chapter reveals the components of the architectural Data-Driven Operational Framework and shows the connection between them. The chapter supports the construction of this framework with an explanation of the different components and processes. This explanation leads to the recognition of the levels of data intervention in architectural design and business. These levels are identified and discussed in this chapter. Finally, the impact of *Big Data* and the *Internet of Things* on the industry is proposed based on the identified changes in the business models, cultural models and value.

For the second aim, the chapter represents a validation of the Data-Driven Operational Framework through a Grounded Theory validation. This validates the research output and analysis.

The main output of this chapter is:

- The Data-Driven Operational Framework.
- The Data-Driven Levels in architecture operations framework
- The Data-Driven Impact on the AEC industry framework.

5.1. The Data-Driven Operational Framework in Architecture

The Data-Driven Operational Framework resulted from the Selective Coding process of the Grounded Theory. This framework includes all the operations and components needed for adopting a data-driven approach. Four categories emerged from the Selective Coding: Peripheral Data, Recognition, Intervention and Application. Each of these categories has its own components.

a. Peripheral Data

This category contains the raw data that can be queried. The data is either Stored, Real time or Future (Predicted). Table 53 shows these data types and their definitions.

Table 53 Peripheral Data Types

Data Components	Definition
Stored	Data saved in a database.
Real Time	Data streaming from the source.
Future	Data simulated in an application or software.

b. Recognition

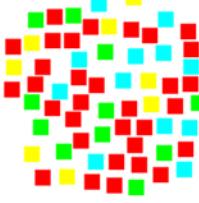
This is the methods of recognising and making sense of data. It also refers to the different operations that are performed on data for an Intervention to allow an Interaction. The recognition is divided into four types: Collection and Gathering, Aggregation and Processing, Analytics, and Modelling. Table 54 provides a definition of each process. Table 55 shows a conceptual representation of the data processes.

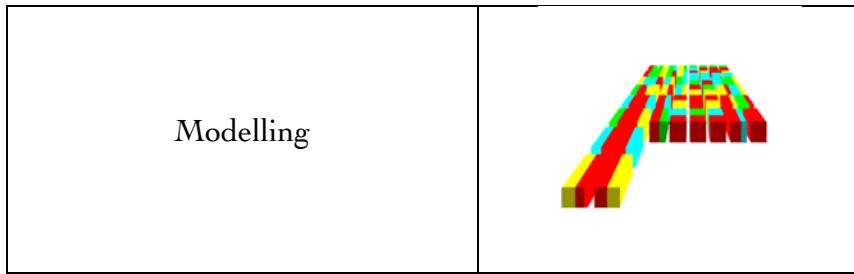
Table 54 Operations Definitions in Data-Driven Models

Process	Definition
Collection and Gathering	The simple process of collecting and gathering data of all types with no operations performed on the data.

Aggregation and Processing	The process of selecting and deselecting certain types of data for initially identified proposes.
Analytics	The process of coding, applying algorithms, and connecting certain types of data following a set of rules.
Modelling	The process of transforming data from one format into another, such as visualising text and numeric data.

Table 55 Representation of Data Operations

Raw Data	
Collection and Gathering	
Aggregation and Processing	
Analytics	



c. Intervention

The intelligence responsible for recognising data and making sense of it. The Intervention has three levels: Human-Enabled, Computer-aided Enabled and fully Automated. Table 56 defines these levels.

Table 56 Intervention Sources in The Data-Driven Models

<i>Intervention</i>	<i>Definition</i>
<i>Human-Enabled</i>	The data recognition is happening based on human intervention, with no computer or machine aid.
<i>Computer-aided Enabled</i>	The data recognition is happening based on human intervention with assistance from a computer or machine.
<i>Automated</i>	The data recognition is happening based on the intervention of a computer or machine with no human intervention.

d. Application

The output medium by which data is delivered and can be interacted with. The types of output application of data-driven operations are Interface, Smart Materials and Kinesis architectural elements. Table 57 defines these applications.

Table 57 Applications of Data-Driven Operational Models

<i>Application</i>	<i>Definition</i>
<i>Interface</i>	A device or program that allows direct human interaction with data.
<i>Smart Materials</i>	A material that reacts and changes its properties according to certain data streams. Nanomaterials are examples of these smart materials. Humans interact with data through this material.
<i>Kinesis Element</i>	Kinesis as a term is derived from the field of biology. Kinesis is “the movement of an organism in response to a stimulus, but not directionally oriented toward the source of stimulation” (Biology Online, 2016). This term is used to refer to the automated architectural and building elements that move and adjust their form in response to a stimulus that is registered through data recognition. The building is seen as an organism where data transfers messages and moves in the compound system.

All together, these components form the Data-Driven Operational Framework. Figure 68 shows the components and the sub-components related to them in the framework. The same figure has the colour codes presented in Chapter 5, section 4.5.

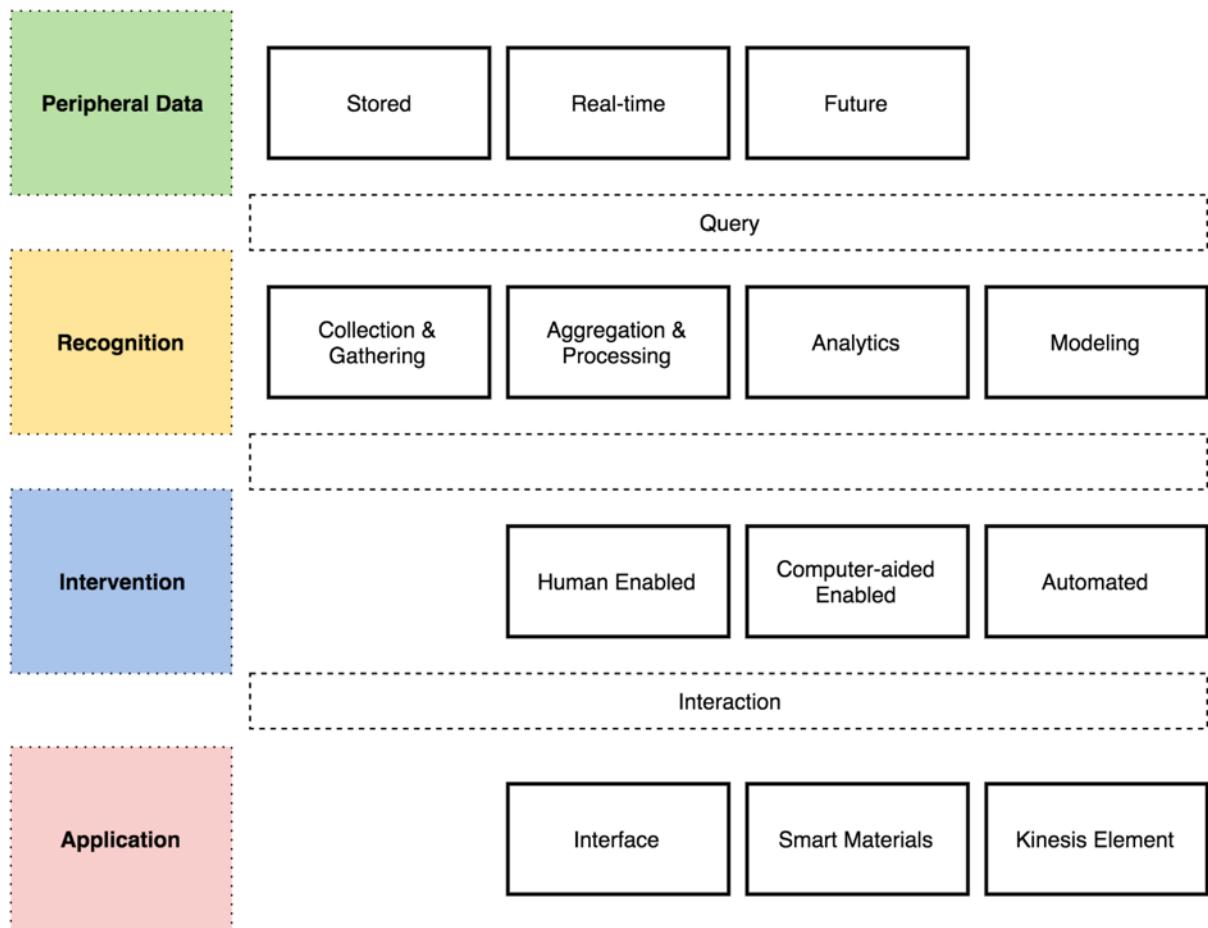


Figure 68 The Data-Driven Architecture Framework

5.2. The Data-Driven Levels in architecture operations framework

The Data-Driven Levels in architecture operations framework is one of the core concepts that resulted from the Grounded Theory analysis. It is a framework that explains the levels of achieving a fully autonomous data-driven design and operation in architecture. Establishing this framework is based on the knowledge implemented in the Data-Driven Operational Framework.

The developed Data-Driven Operational Framework provides an understanding of the various levels of data operations in architecture design and business process, which are pointed out. Utilising the developed diagram of the framework (Figure 68 above) and the recognised understanding of the autonomous level of data operation of each case study allows the recognition of specific components which contribute to the data-driven operation in that case. The same diagram is used to communicate these different levels by highlighting the active components with

colours. These diagrams are conjoined with the descriptions of the levels in the following sections. It is important to mention that six data-driven levels are identified: Level 0, Level 1, Level 2, Level 3, Level 4 and Level 5. The following sections explain these levels.

5.2.1. Explaining the Levels

The following sections explain these levels. And each Level is supported with two diagrams. The first diagram explains how that level is realised from the Data-Driven Operational Framework. The second diagram reveals the shift of data operations between the designer and the computer.

Level 0

This level of implementing data in architecture business and design is the conventional level which exists and has existed since the beginning of the profession. The intervention of data is enabled by a human through his or her recognition and taking decision-making ability. Although the recognition of data happens through collection, aggregation and analytics, it is all based on the human's capacity, experience and knowledge. The data in here is *Small Data* as a counter terminology to *Big Data*, which is small enough for human comprehension. This level of data does not require an application and happens in the human brain. Also, it applies to all design phases. Figure 69 shows the active components in Level 0 in colours. Figure 70 shows the data operations between the human and the computer; it is clear that the computer has no role in this level.

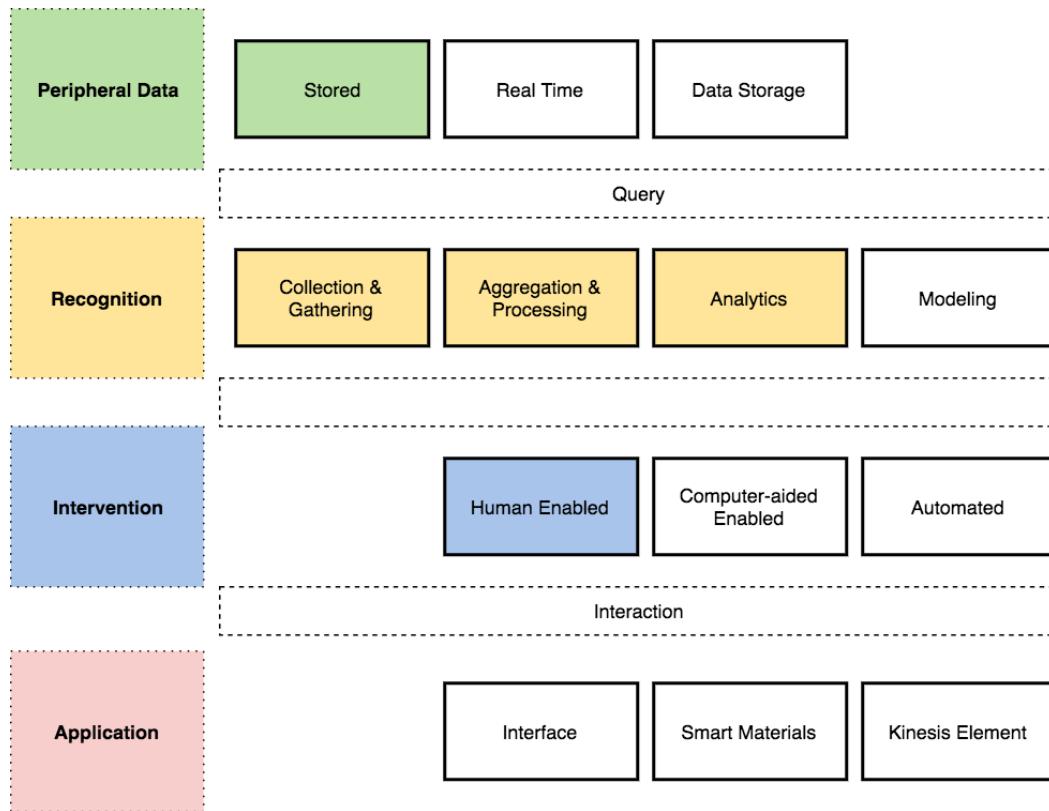


Figure 69. Level 0 of Data Intervention

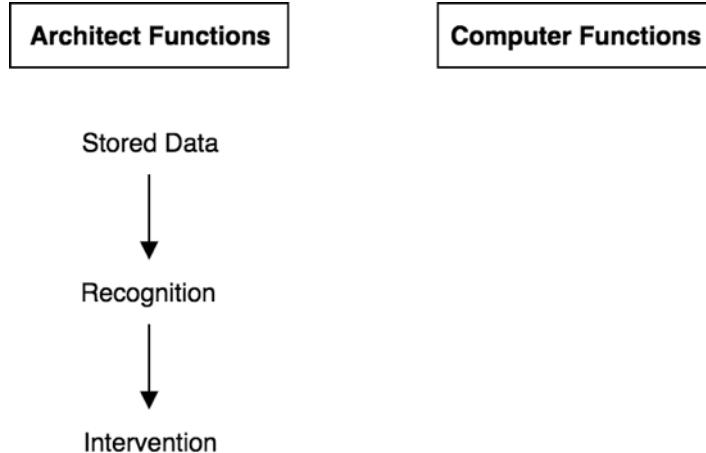


Figure 70 Level 0 Automation in Architecture

Level 1

This level of data intervention in architectural design and business is the basic utilisation of data through the use of digital processes to support design decisions, to give design insights and to allow knowledge discovery to take place. The data here is collected from data sources such as sensors or inputted by a human. The

human assigns specific tasks, analytics or parameters to the digital processor. The digital processor complies, calculates and presents the results through an interface that is used by the human. The human translates these results into design actions. In this level of data intervention, part of the analysis and the modelling is achieved by a human as it is not automated. Simulations and Parametric Design are examples of this level of data use. This level of intervention applies more at early and conceptual stages of design. Figure 71 shows the active components in colours. Figure 72 shows the data operations exchange between the human and the computer.

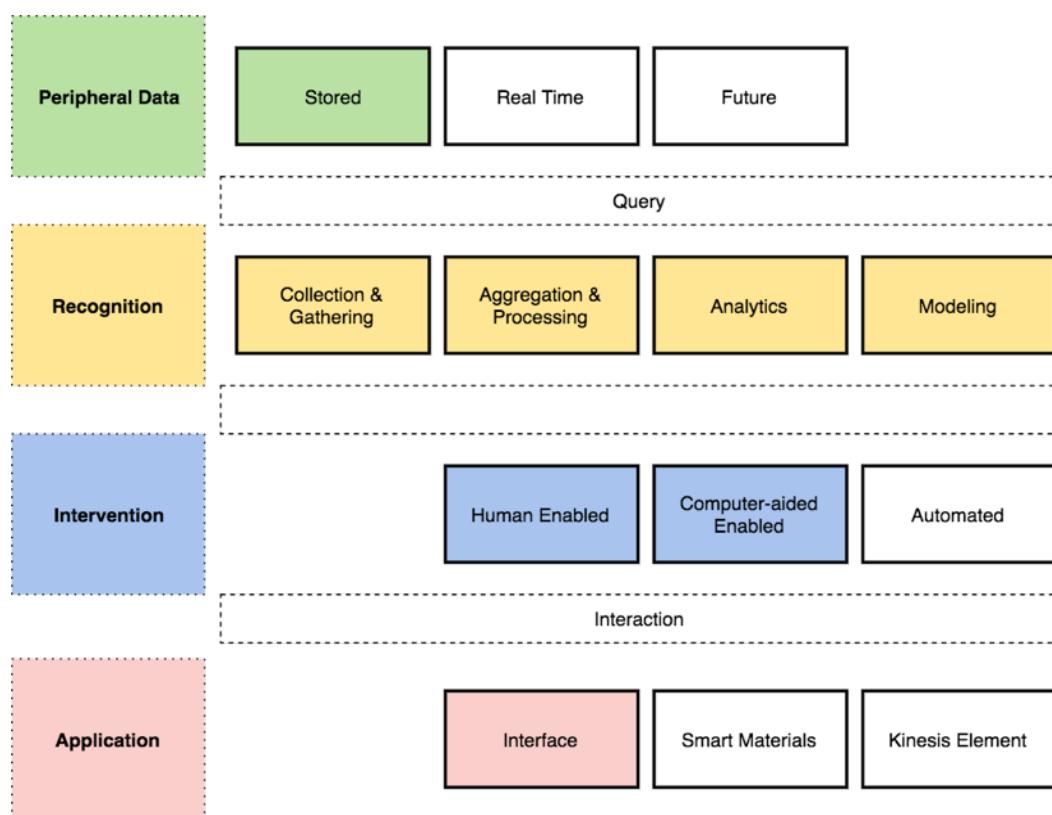


Figure 71 Level 1 of Data Intervention

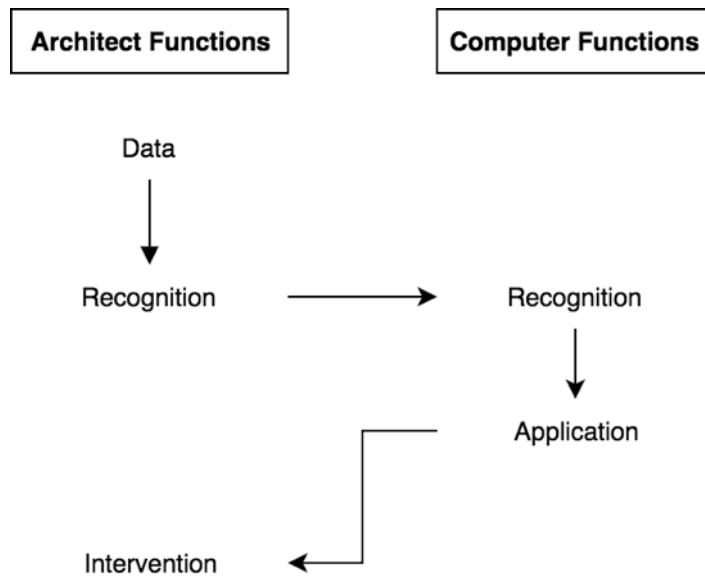


Figure 72 Level 1 Automation in Architecture

Level 2

This level of data intervention is advanced in term of utilising and processing. Stored data is joined with real-time data from buildings and occupants. This data is simultaneously collected, processed, analysed, modelled and translated into information that is presented on an interface. The whole built environment acts as a passive ecosystem of information and communication data with no human involved in recognising or collecting this data. However, at this level, the existence of the human in monitoring and supervising the operation is necessary at the end of the process, for intervention. This level is the first step to establishing datasets and data warehouses for the built environment for a future fully automated data intervention. This level indicates the start of the utilisation of *Big Data* and the *Internet of Things*. Figure 73 shows the active data components of this level in colours. Figure 74 shows the data operations exchange between the human and the computer; it shows that the human and the computer have an almost equal role in the intervention.

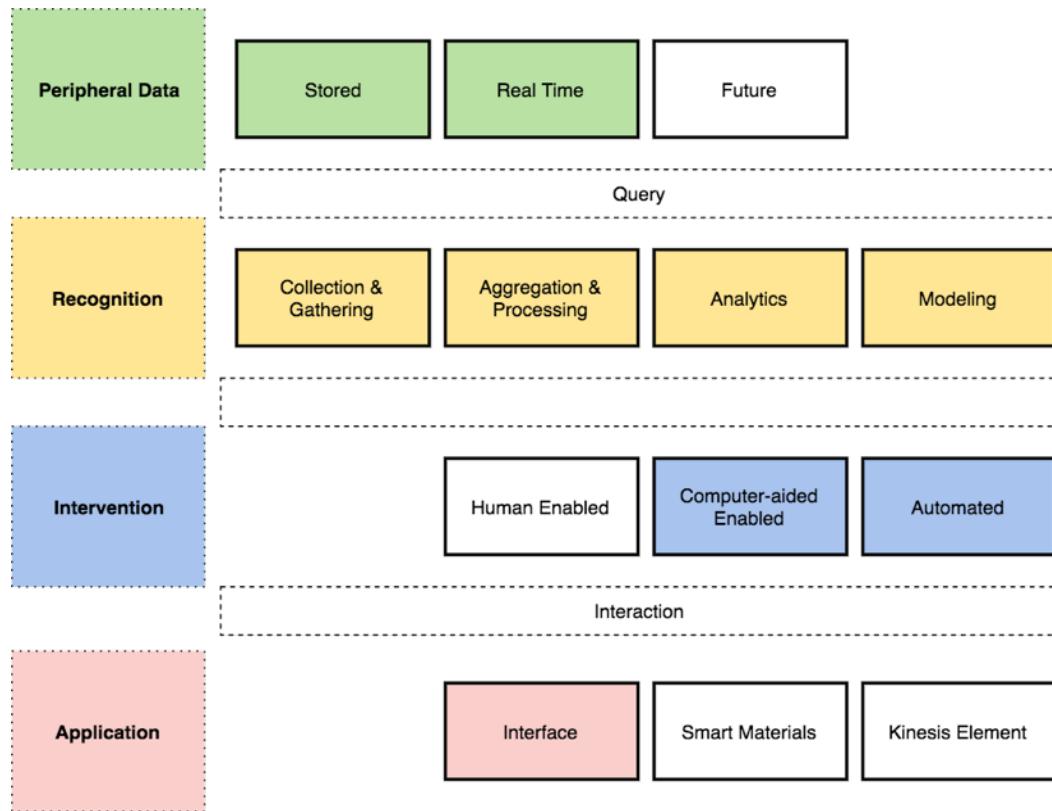


Figure 73. Level 2 of Data Intervention in Architecture

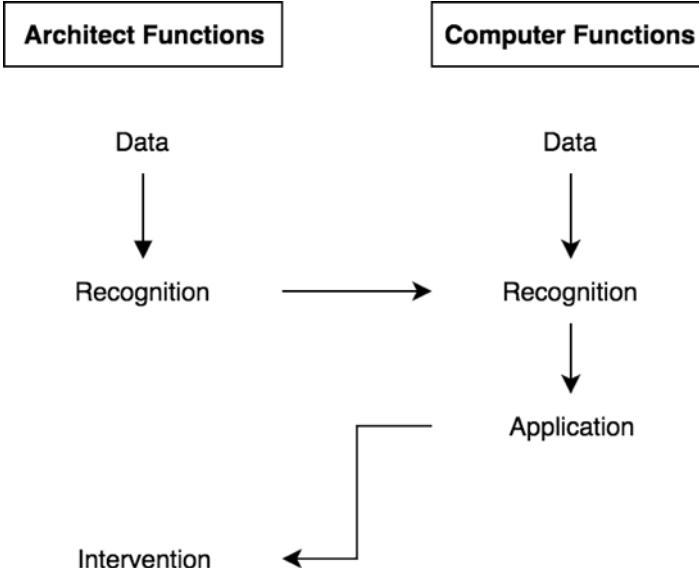


Figure 74 Level 2 Automation in Architecture

Level 3

Level 3 of data intervention in architecture allows the building to operate automatically according to specified parameters assigned by the architects. The building becomes an organism of connected networks and databases. This data effect extends beyond the adjustment of the mechanical systems and the refinement of the internal environment properties to affect the external envelope through smart materials and Kinesis elements. In this level, an interface is still available to enable the human to override or adjust the system. However, the building is smart enough to register any overriding entry and to recognise the modification associated with it, to utilise this modification later for future purposes according to the occupants' needs and preferences. A large amount of data is created, stored, simulated and analysed for more accurate intervention. Figure 75 shows the active data components in colours. Figure 76 shows the data operations between the human and the computer.

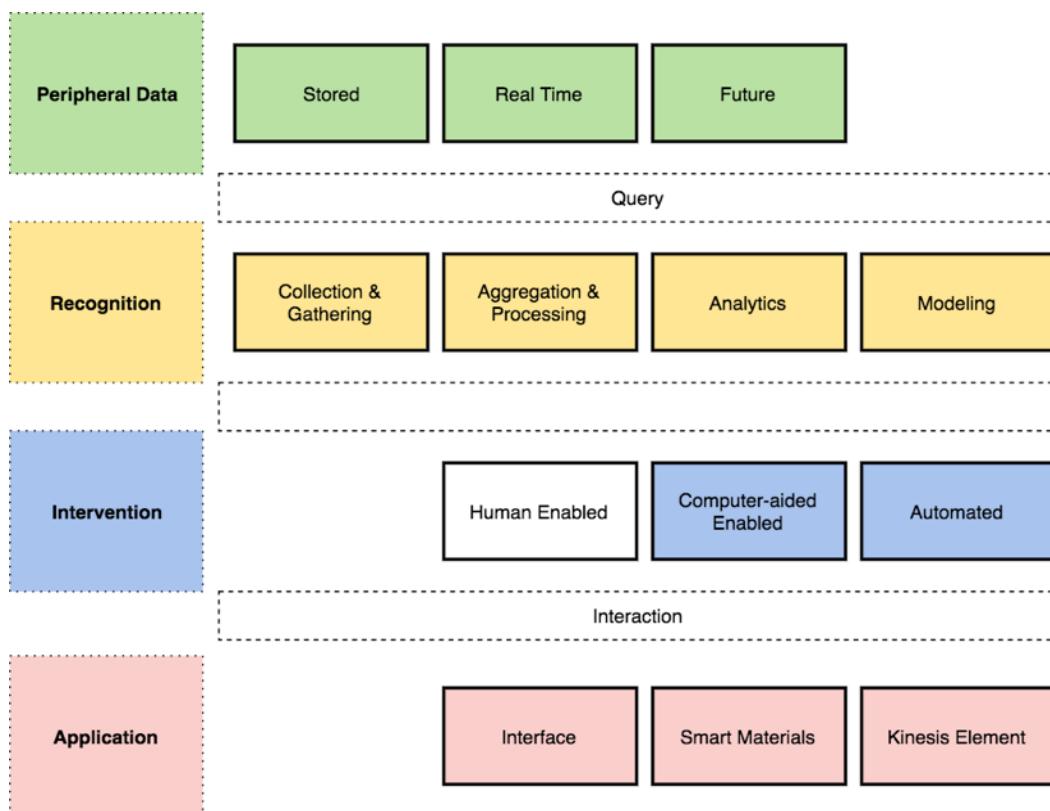
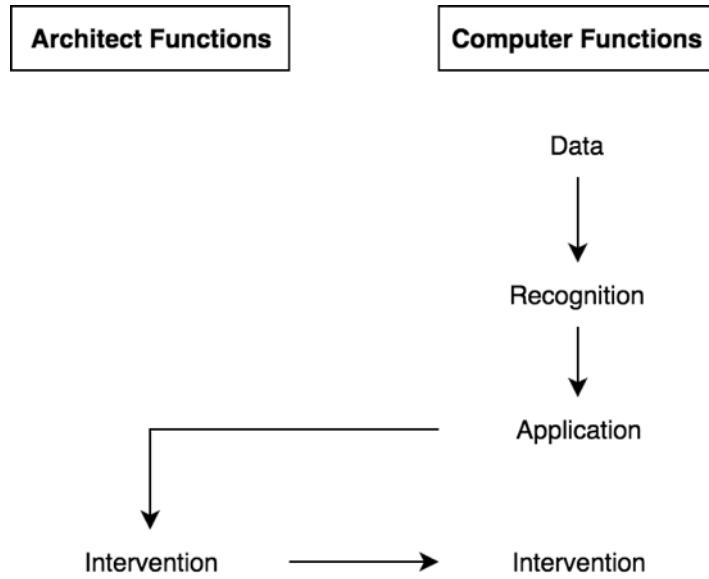


Figure 75. Level 3 of Data Intervention in Architecture

*Figure 76 Level 5 Automation in Architecture*

Level 4

In this level of data intervention, each building is fully data-driven autonomous. A network of connected buildings forms a bigger ecosystem of data intelligence. Buildings communicate together to optimise their performance collectively and adjust their spaces according to their interaction with occupants. The amount of generated and stored data is sufficient to cover every possible future scenario. There is no direct human intervention with data, but an interface is provided for safety override control. Figure 77 shows the active data of this level's components in colours. Figure 78 shows that the data operations are driven by a computer, and how human intervention takes place.

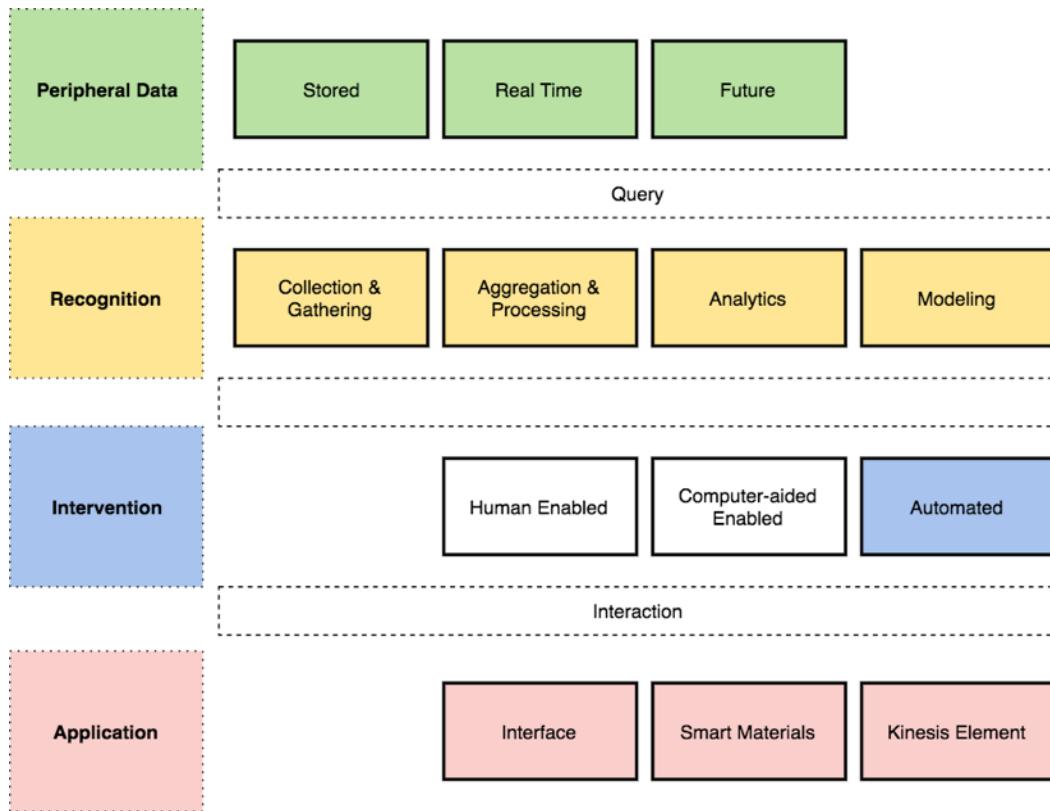


Figure 77. Level 4 of Data Intervention in Architecture

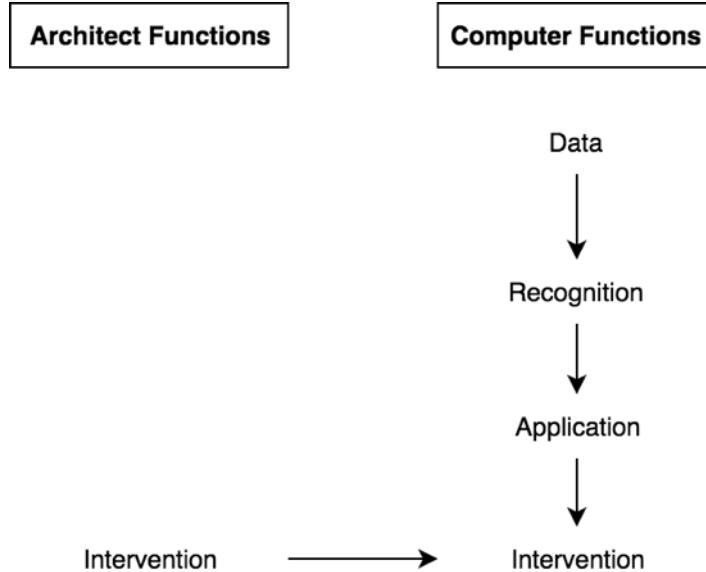


Figure 78 Level 4 Automation in Architecture

Level 5

In this level of data intervention, the intellect of the system and the amount of available intelligent data allows the buildings to re-design and adjust themselves according to the need of the ecosystem. Humans are part of this ecosystem. The system is very complex and revolutionary with regard to data recognition and application. It has no interface as each part of it is communicating information. Although the logic of the data intervention is evident, the method of construction of such a self-designed building remains unclear and futuristic. Figure 79 shows the active components in colours. Figure 80 shows the digital data operations.

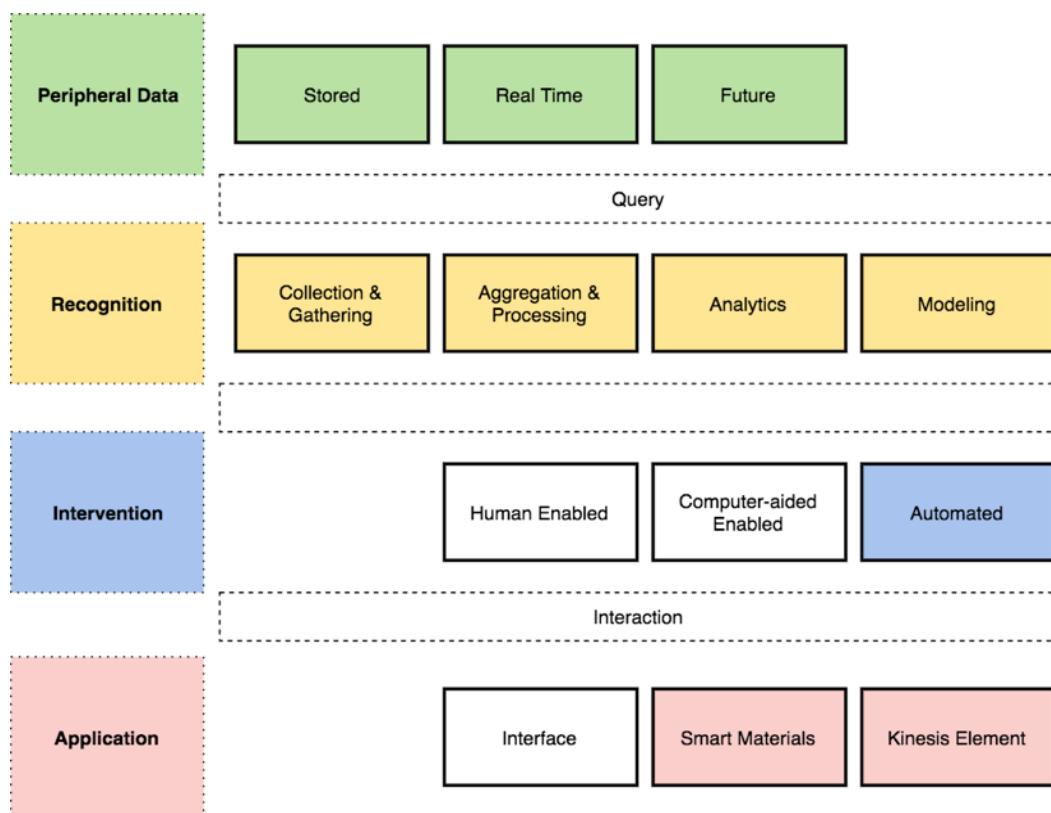


Figure 79. Level 5 of Data Intervention in Architecture

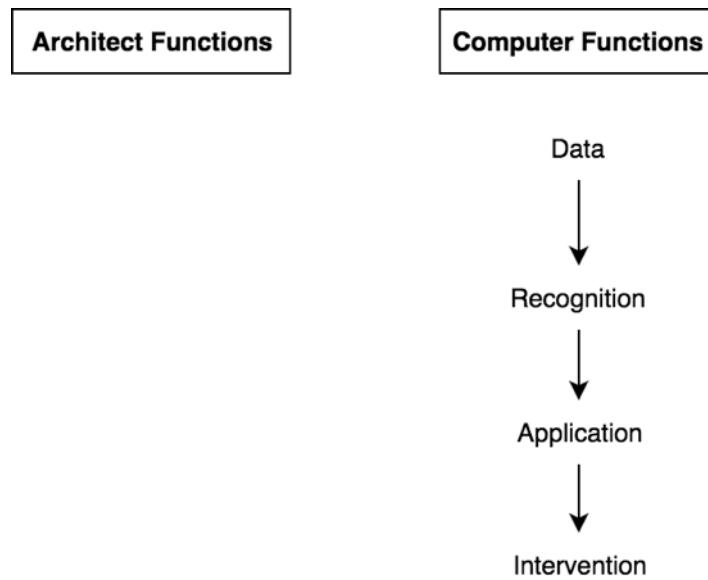


Figure 80 Level 5 Automation in Architecture

5.2.2. Summary

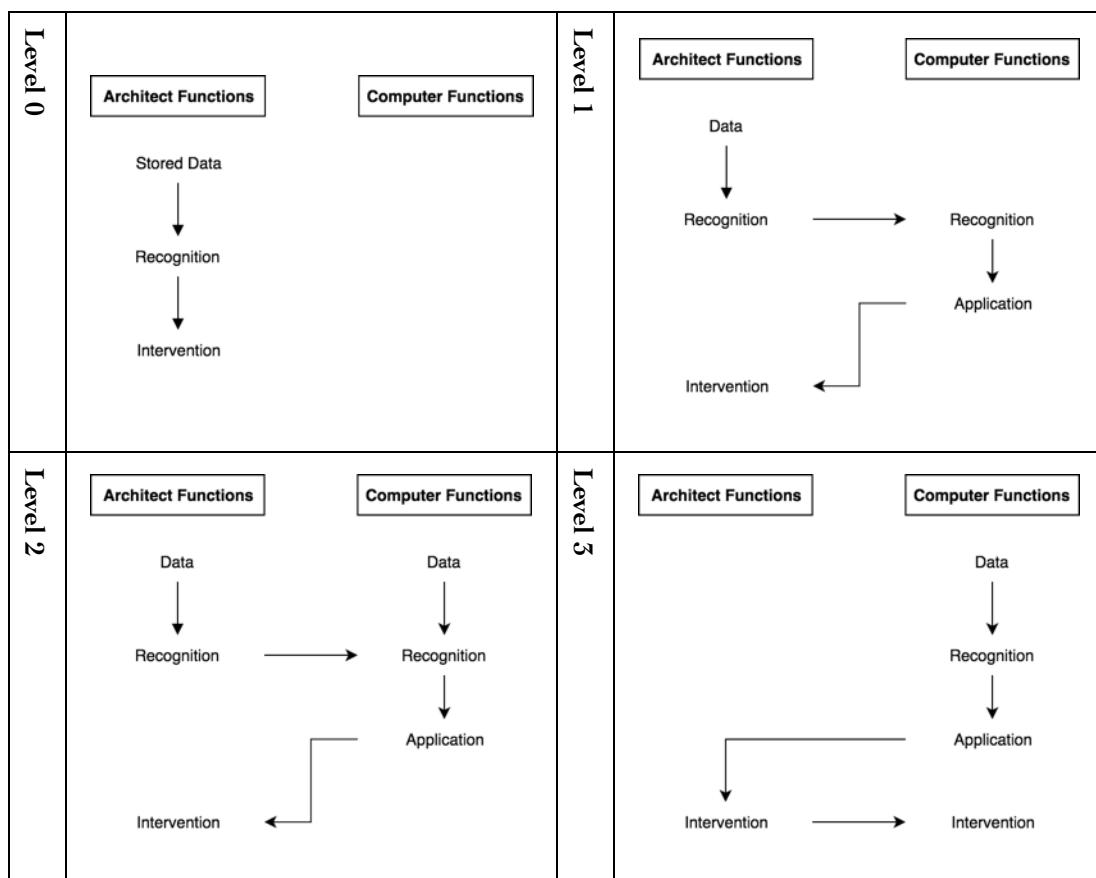
Table 58 and Table 57 show the levels of data intervention in architecture design and the associated diagrams.

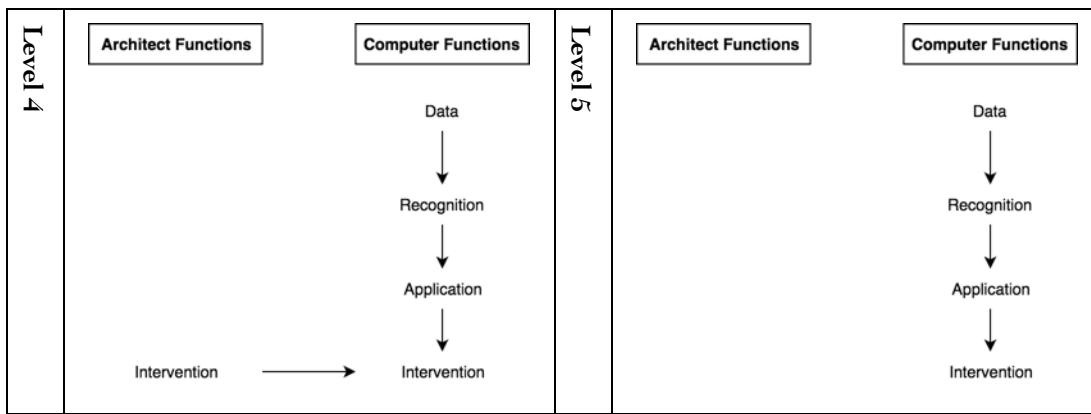
Table 58 The Data-Driven Levels In architectural operations framework

Data-Driven Operational Levels		
Level 0	Design decisions are taken solely by architects and designers.	
Level 1	Parametric design approach allowing architects to take decisions for specific identified problems based on alternatives generated by a computer application or predictive design decisions allowing architects to virtually simulate certain circumstances and test the decision in a computer environment.	
Level 2	The building work as a data ecosystem, providing real-time information about operations, occupants and conditions. The building allows end-users to monitor certain operations and acts as a data generator for future use.	

Level 3	Automated building operational under defined conditions. The building changes its configuration through specific smart materials and architectural elements. Occupant intervention is in place.	
Level 4	Fully automatic building acting as a node in a network of other buildings or as a part of the urban configuration.	
Level 5	Self-designed building based on analysis from the data eco-system applied to a specific location.	

Table 59 Levels of Data Automation in Data-Driven Models





5.3. The Data-Driven Operations Impact on the AEC Industry framework

The other core concept that resulted from the Grounded Theory Coding analysis is the Impact Models of data-driven design in architecture, Engineering and Construction. *Big Data* and the *Internet of Things* are disruptive technologies in the AEC and affect the current adopted business and cultural models. This impact requires an adjustment and refinement of these models. This refinement will allow new digital values to emerge.

The following business models are utilised to describe the impact of Data-Driven operations on the AEC: Design, Build, Post-Occupancy, Design-Build and Integrated. Also, a new model of operation (Inter-Connected) is proposed. These models are discussed in the following sections. At the end of these sections, Table 60 summarises the discussion and shows the impact of Data-Driven methods on all the AEC business and cultural models.

5.3.1. The Impact of Data-Driven Operations on the Design Model

The employability of data-driven operations in design allows the expansion of the promised values in design. This could be reflected in the design contract by providing an interdisciplinary valuation method which is based on data integration and offering an Evidence-Based validation. This contract has the potential to adjust the current architectural service and Fees-For-Services by proposing data-bundled payment models. These changes affect the overall design workflow by increasing the use of data in current workflows or introducing wholly new data-driven ones.

The architects are required to be equipped with particular digital skills. This data-driven design model has the potential to involve all end-users (occupants) in the early design process.

5.3.2. The Impact of Data-Driven Operations on the Build Model

A Data-Driven Build model has the potential to offer an efficient execution of the construction process by providing better tools for operation, communication and costing. The impact advances Telematics and Real-time locating systems as a core part of the build operation along with Building Information Management tools. These technologies are part of an improved data integration that hosts data from construction equipment and workers. The data integration provides better communication between project managers and other involved parties and provides a platform for producing more accurate project scheduling and cost control. This universal approach to data allows better collaboration between all stakeholders, especially sub-contractors and vendors.

These changes require the general contractor to be digitally competent and have access to such data technologies and a unified platform. The impact of a data-driven Build model has great potential to: enhance security and safety; improve quality control and logistics; and support better administration and organisation. These all contribute to a more efficient construction process.

5.3.3. The Impact of Data-Driven Operations on the Post-Occupancy Model

Data-driven operations allow the contract to be extended to a post-occupancy phase of the architectural project as architects remain connected to the built design through data. This model resembles a new Post-Occupancy model which is more advanced than Post-Occupancy Evaluation (POE) and goes beyond the feedback cycle and evaluation. This model emerges due to the introduction of smart data-driven materials and architectural elements that allow a digital connection to be established between the architect and the architecture space. The data-driven materials and architectural elements can move and can change according to the data feed they receive. Having an architect to monitor this data feed becomes essential to guarantee optimum space performance. Also, this model allows a better use of

location and tracking technologies by enabling a virtual mapping and monitoring of space that allows the utilisation of smart technologies such as smart home devices.

This model introduces a new role for the architect as a facilitator and involves him or her in Facility Management and Operation. This role requires new skill sets. The value of this model relies on providing an intelligent interaction between the occupants and the built environment that is monitored and optimised by the architect. This interaction can promote behaviour changes in occupants and provides accurate feedback for better future implementation or future builds.

5.3.4. The Impact of Data-Driven Operations on the Design-Build Model

This model has the potential to exploit the true potency of the data-driven operations in the architecture business. The model has an advanced level of data integration where architects and contractors are part of the same data ecosystem and platform. This model is a combination of the Data-Driven Design and the Data-Driven Build models, and maintains the impact of both. The data ecosystem brings architects and contractors together from an early stage of the project. Architects and contractors exchange Batch and Real-Time data that is used in managing the building information and engage in effective collaboration for better execution and management with regard to value implementation, time and cost.

5.3.5. The Impact of Data-Driven Operations on the Integrated Model

This is an advanced model of data-driven collaboration. It aims to bring all stakeholders together from an early stage of the design and construction process. Architects, contractors, owners and occupants operate using data through an advanced ecosystem. The ecosystem is based on value delivery and measurement. This model proposes a change in the business to a Value-Based Assessment and Pricing by introducing value metrics to measure the overall project performance. This model requires all stakeholders to extensively and simultaneously collaborate about the project values with no regard to the phase and the stage of construction. This model addresses and aims to resolve all communication barriers in the construction industry through focusing on the values. This model allows all the concerned parties to align their overall business value with the project values.

5.3.6. The Impact of Data-Driven as the Inter-Connected Model

A universal approach for an Integrated Data-Driven Model where metrics and data are shared locally and internationally. The building is connected to a broader data ecosystem of other buildings within the region. This model requires a higher level of collaboration between all stakeholders and non-stakeholders on a wider basis. It aims to achieve optimum values for the business, the project and the environment.

5.3.7. Summary

Table 60 reviews the discussed models and the impact of adopting a data-driven operation in the AEC.

Table 60 Data-Driven Implementation Models in The AEC Industry

Data-Driven Operational Models in the AEC industry	Business Impacts	Cultural Impacts	Observed Value
Design	Adjustment to the architectural service and the Fee-For-Service models based on an added-value contract that allows bundled payment to take place.	Introduction of a data-enabled workflow to the current architectural model.	Refined functional and operational design ideas that engage end-users (occupiers) and predict behaviours.
Build	Investment in Telematics and real-time locating systems for material, equipment and personnel accompanied with Building Information Management. A higher profitability to the builder through the efficiencies gained.	The project manager is required to use a data ecosystem and enable collaboration between subcontractors and vendors in a way that is much more integrated.	Enhanced site security and safety, improved quality control, better worker logistics and scheduling, more organised, more efficient construction process.
Post-Occupancy	Additional fee-for-service models using animated smart materials	Involves architects in the facility operations where data streams are the	Further interaction with the built environment. Stimulates behaviour

	and elements, in addition to the use of tracking systems.	connection with occupants.	changes in occupants. Promotes efficient use. This use of data allows the creation of a Built-Environment data warehouse.
Design-Build	The utilisation of a shared data ecosystem between architects and builders, in addition to the Building Information Management collaboration.	Early extensive collaboration through the design, the construction and the supply chain.	Owners and occupants will see benefits regarding better value, time and cost.
Integrated	Involves all stakeholders in creating a value system to assess the project. The business model is based on value delivered over time (Value-Based assessment).	Requires all stakeholders to collaborate extensively and simultaneously to achieve the project values.	Addresses all communication difficulties in the construction industry. Allows all stakeholders to align their business values with the project values.
Inter-connected	The building is connected to a wide data ecosystem on a regional scale.	Highly collaborative on a region level.	The ultimate development of design as a data-driven business.

In the previous sections, the results of the analysis were reported and discussed. The sections covered how these results emerged and how they are connected. The sections reported the Data-Driven Operational Framework, the Data-Driven Digital Value Equaliser, the Data-Driven Levels in architecture operations framework and the Data-Driven Impact on the AEC industry's models framework.

In the following section of this chapter, the validation process according to the Grounded Theory is presented to support and validate the results of the analysis.

5.4. Case Testing

The case chosen for this testing is ‘Ada: Playful Intelligent Space’ by ETH Zurich. This case represents an Urban Interactive space which allows data to drive the interaction of the space’s occupants. This case was chosen based on the original criteria of selecting the case studies, however this case brings new variables that show the emergent of new factors in the Data-Driven Process. and this contributes to the validity of the case.

The analysis was conducted based on a textual description of the design and operating process in order to extract keywords that matched the concepts developed in the operational framework and their relationships. The following figure shows the initial analysis (Figure 81, Figure 82).

1. The Ada Project

Ada is an interactive space developed for the Swiss national exhibition Expo.02 located in Neuchâtel. Conceptually, “she” can be seen as an inside-out robot with visual, audio and tactile input, and non-contact light and sound effectors. Visitors to Ada are immersed in an environment where their only sensory stimulation comes from Ada herself (and other visitors). Like an organism, Ada’s output is designed to have a certain level of coherence and convey an impression of a basic unitary sentience to her visitors. She can communicate with them collectively by using global lighting and background music to express overall internal states, or on an individual basis through the use of local light and sound effects. To realise such a space, several simultaneous lines of research and development were pursued. Topics under investigation include:

- Audio processing and localisation
- Multi-modal tracking
- Automatic music composition
- Real-time neuromorphic control systems
- Human-machine interaction via whole-body locomotion

2. Sensors, Effectors and Core Services

In total (including auxiliary exhibition areas), Ada has 15 video inputs, 367x3 tactile inputs, 9 audio input channels, 46 mechanical degrees of freedom, 17 output audio channels, 367x3 floor tile lights, 30 ambient lights and 20 full-screen video outputs. All of these inputs and outputs can be addressed independently, giving a rich array of sensory modalities and output possibilities.

3. Behaviours and Interactions

The degree of success with which visitors can be convinced that Ada is an artificial organism depends on the nature of their interactions. The operation of the space needs to be coherent, real-time, and reliable enough to work for extended periods of time. As well as this, it must be understandable to visitors and sufficiently rich in the depth of interactions so that visitors feel the presence of a basic unitary intelligence. To provide for a natural progression in visitor interaction, Ada incorporates at least four basic behavioural functions. First, she can track individual visitors or groups of visitors, possibly (but not necessarily) giving them an indication that they are being tracked. At the same time, she can identify those visitors who are more “interesting” than others because of their responsiveness to simple cues that Ada uses to probe their reactions. These people are encouraged to form a group in part of the space through the use of various light and sound cues. When the conditions are appropriate, Ada rewards a group of visitors by playing one of a number of games with them. She continuously evaluates the results of her actions and expresses emotional states accordingly, and tries to regulate the distribution and flow of visitors. These four behavioural functions are decomposed into smaller behaviours that call on the core services as needed.

Figure 81 The Initial Analysis of The Textual Description of The Test Case (Eng Et Al., 2005)

The initial coding highlighted the words that hold the semantics of the concepts of the data process in the case. Subsequently, these concepts were related and connected through the proposed Data-Driven Operational Framework. The

exposed relationships revealed the hidden understanding of the data-driven process within the interactive space. This uncovering would not have been possible without the proposed framework presented in Figure 68 which shows the extraction of the concepts and their relationships according to the Data-Driven Operational Framework. All coded words fitted within an Axial Coding category which reflected one of the framework components. However, a new Axial Coding “Gamification” category emerged from this case analysis. This category is related to the “Application” component and is expressed through an “Interface”. “Gamification” refers to using games for other purposes than their expected use for entertainment (Deterding et al., 2011). In this case, games were used to keep visitors engaged, as the text indicated. This regulative technique is dependent on constant monitoring and data collection. Without the existence and accessibility of *Big Data* techniques, this implementation could not happen (Schrape, 2014).

Clarification regarding “effectors” and “lights output” keywords is necessary to explain the coding process. Both keywords indicate outputs of certain changing properties: one is audio and the other is light. Although the change in the materials’ properties is slight and it is not considered entirely smart – as in advanced materials and nanotechnology - it was still coded as part of “Smart Materials” with consideration of a hypothetical existence of a smart materials spectrum where these outputs are placed at the beginning.

In Figure 82, a representation of the keywords extracted from the text and the Open and Axial Coding that is applied to construct the concept.

Open Coding	Keywords	Axial Coding	Concepts
Data Source	Visual, audio and tactile input	Input - Real Time Data	Peripheral Data
Data Handling	Non-contact light and sound effectors	Output - Smart Materials	Application
Data Handling	Communicate collectively and individual	Interaction - Output	Application
Data Handling	Audio processing and localisation	Processing/Modelling	Recognition
Data Handling	Multi-model tracking	Analytics	Recognition
Data Handling	Real-time neuromorphic control system	Processing	Recognition
Data Offering	Human-machine interaction	Interaction	Recognition
Data Source	Inputs, inputs, input	Real-time	Peripheral Data
Data Offering	Output	Smart materials	Application
Data Offering	She can track	Automated/Collection	Intervention/Recognition
Data Offering	She can identify	Automated/Aggregation	Intervention/Recognition
Value Preposition	Ada rewards	Computer-aided/Gamification	Application
Data Offering	She Continually evaluate	Automated/Analytics	Intervention/Recognition

Figure 82 The Extraction of The Concepts and Their Relationship According to The Data-Driven Operational Framework

The active Data-Driven Operational components are highlighted in the following figure (Figure 83).

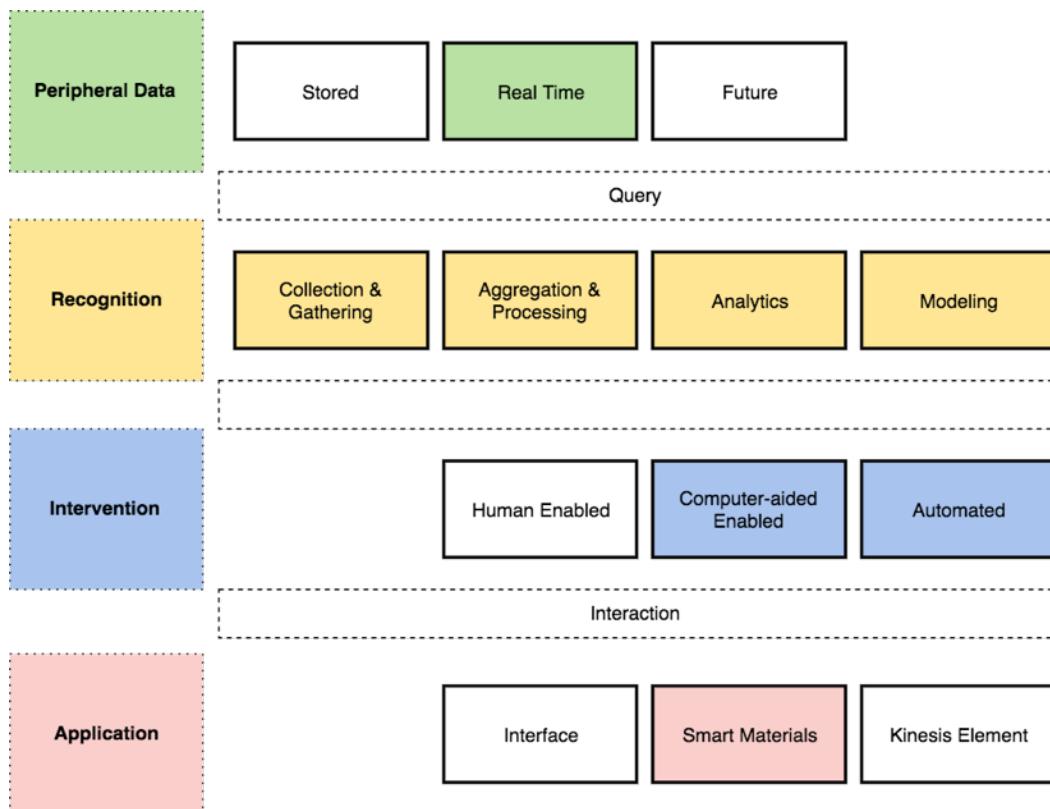


Figure 83 The Data-Driven Operational Components in The Test Case

Moreover, the extracted concepts which revealed the data-driven process were used to identify the level of data operation in the case with the assessment of the proposed Data-Driven Operational Levels Framework (Table 58). The data intervention shows a derivative of Level 2 data operation that utilises “Real Time” data without storing it and proposes an application through “Smart Materials” rather than an “Interface”. The Data-Driven Operational Framework clarified the data processes of driving the space and allowed the different components to show, in addition to the new category “Gamification”.

5.5. Framework Validity

The research developed a Grounded Theory of how data drives the architectural design and business process, which led to the proposal of the Data-Driven Operational Framework. The earlier criteria specified by Glaser (1968, 1998) were used to assess the Validity of this framework. The framework meets the assigned criteria and demonstrates the characteristics of fit, relevant, general, workable and modifiable. First, the framework proved adequate in expressing the pattern in an architectural design context and could conceptualise it when new related cases were considered (fit). Also, the concepts are sufficiently related and connected, allowing a clear understanding of new data-driven operations in the architectural context (workable). Secondly, the framework is comprehensible and appeals to the architectural design and business as it was derived from there (relevance); in fact, it expands to appeal to the whole AEC industry - as the proposed change in business models suggests - and the IT sector (general). Thirdly, the framework proved flexible as it was expandable and modifiable, allowing new patterns and concepts to emerge, as seen in the test case (modifiable). These all confirm the validity of the proposed framework and the applicability of the Grounded Theory approach.

5.6. Data-Driven Design Applications and Innovations Summary

The previous sections presented the process, the analysis and the results of the Grounded Theory methodology executed in the context of data integration in architectural design and business. A framework for data-driven operation was proposed and validated. The framework led to identification of the different levels of data implementation in architectural design and business, and this prompted the

investigation of the impact of such technologies on the current architectural business and cultural models.

All this evidenced that Data-Driven technology and techniques allowed other technological applications and innovation to follow in architectural design and business. A list of the new applications that depend on data-driven operations was identified from the analysis and presented. These innovations outline an area of research on their own. Investigating them lies beyond the scope of this research, but they provide prospects for future research:

- Massive Passive User Participation
- Urban and Architectural Gamification
- Big Building Information Modelling and Management
- Data Designs Fusions and Architectural Design Matrix

Figure 84 shows the use of coding procedures of the Grounded Theory Methodology and their contribution to the analysis in the research.

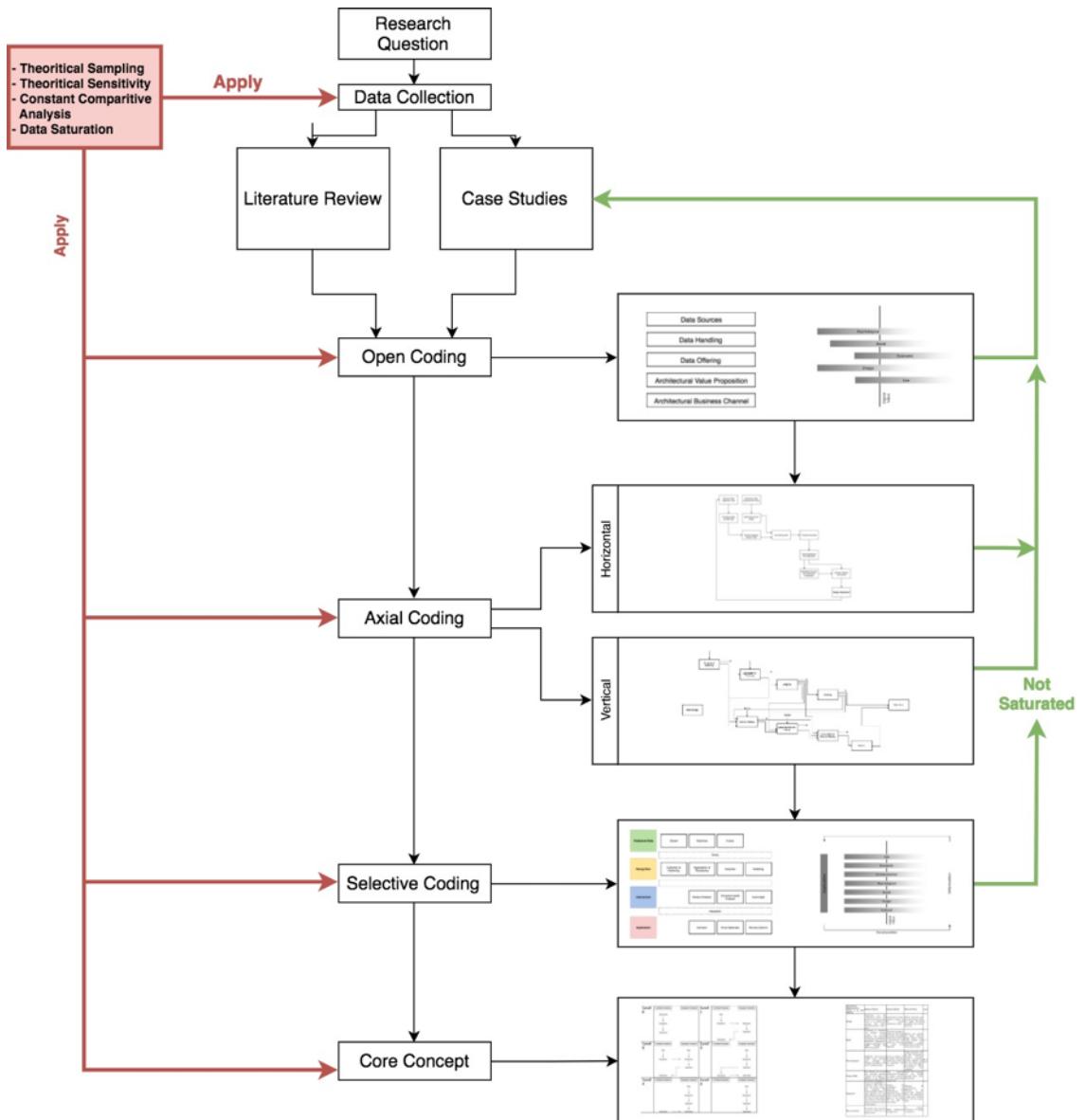


Figure 84 The Use of The Grounded Theory Methodology in The Thesis

Chapter 6: Conclusion

This research emphasises the necessity of reconsidering architecture from a business perspective that is based on a profound understanding of the value inherited from utilising emergent data technologies such as *Big Data* and the *Internet of Things* in the design and decision-making processes. Another emphasis is the focus on value and proposing a value analysis of the built environment. The critical understanding of the acquisition of value that is achieved by data technology, and the correlation between data and value proved the need to develop new operational models to adopt in the architecture practice and business. These operational models enhance the design, expand the industry impact and increase the overall attained value in the built environment.

The research contributes to the objective of acquiring more value through data-driven technologies by the development of a data-driven operational framework which encompasses the various data processes and incubates the value of adopting a data-driven approach in architectural design and business. The framework contains the different data-driven operational components and reveals the connection between them by defining and relating them in accordance to their properties and hierarchy in an application with a controlled context that is presented in case studies.

In this chapter, a summary the main findings, the research validity and the research contribution is presented.

6.1. Main Findings and Summary

The research was carried out with the intention of fulfilling the following objectives:

- Identify the definition and the possible use of *Big Data* in architectural businesses with the objective to capture its potential.
- Investigate Value in the built environment to assess how data technologies contribute to this value.
- Critically assess and analyse existing cases that present efforts to integrate data through the design process to understand current methods, technologies and values.

- Define the main components of data-driven operational models that exist in other industries and contexts and transfer these components to be used in the architectural practice.
- Develop a data-driven operational framework for the architectural practice which assists data integration as part of the design, and support data-driven business models and bring more value to the practice itself and the built environment.

These objectives were achieved through the various chapters as the following diagram (Figure 85) shows.

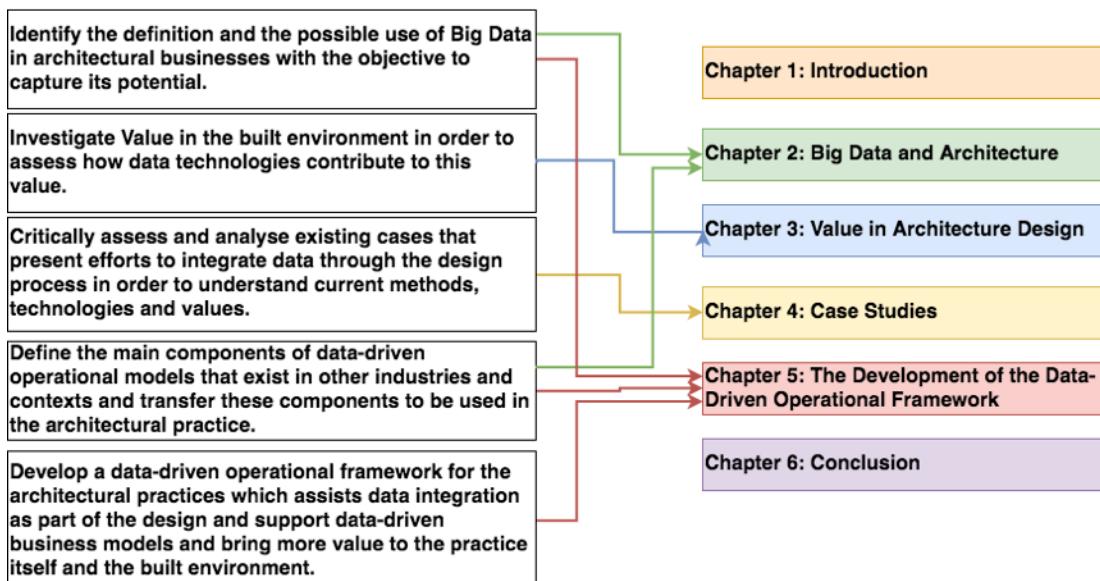


Figure 85 Research Objectives in Relation to the Chapters

An overall understanding of the state-of-the-art data technologies was essential to establish the fundamental knowledge of data-driven operations. The fundamental knowledge included terms, definitions, taxonomies, and the potential and the advantages of using data-driven techniques. This knowledge showed the state of data technologies outside the architectural industry. Also, it allowed the recognition of the current architecture position in utilising these technologies. Architecture as a practice had limited access to the use of such technologies. This was attributed to the following: the current culture of architecture as a process; the constrained context associated with buildings as an artefact; the continuous interaction related

to the occupancy of architecture; and the ambiguity of value creation and delivery in architecture. The understanding that "data is all about value" highlighted the necessity of understanding value.

The thorough examination of values and value taxonomy in the built environment revealed an aspect of the design process that was related to the decision making. Values dictated architectural decisions, movements, styles, objectives, criteria and synthesis in design and business. Values depend on various factors; some are related to time, place, context and resources. An introduction to the Digital Value was essential as digital resources exist and are becoming vital in the architectural design process. This Digital Value suggested that architects need to acquire new digital and technological skill sets. Although some of these skill sets are not new, it is becoming necessary to acquire more specialisation in the data field. Also, the Digital Value suggests the emergence of a new type of architect: The Digital Architect, which is added to the current ones (Cultural, Environmental, Social and Commercial). Moreover, some valuation methods were investigated and assessed according to the possibility of allowing data to drive the value, which showed to be possible using specific *Big Data* and the *Internet of Things* applications. The Digital Value revealed the instrumental value and allowed the cases to be assessed based on the data potential it has.

The analysis of the eight cases allowed the emergence of the data-driven models. A Grounded Theory coding analysis of each case has contributed to the understanding of the different models and levels of data implementation and the methods employed. A Horizontal analysis for each case enabled a grounded understanding of each data implementation model and how the data-driven components were connected on an abstracted level across different categories; how these connections and categories were ordered; how humans intervened within the process; how the value was created within the process; and how the process continued. A Vertical analysis related all the data-driven processes together in a hierachal organisation and allowed a universal understanding of data-driven models in architecture. This understanding of data models and concepts was employed to propose a theoretical framework for the use of data in architectural business, which is referred to as the Data-Driven Operational Framework.

Four components of data-driven operational framework in architecture were identified. These components exist in the case studies and continue to exist in all data models in architecture design and business. The four components are Peripheral Data, Recognition, Intervention and Application. Each of these components had sub-components and were linked to each other on various levels of implementation.

The establishment of these concepts and this understanding highlighted the various levels of data integration and permitted the proposal of the Data-Driven Levels Framework in architecture operational framework. This framework defined the six incremental autonomous levels of data integration in the design process. Each level describes how data is processed and the nature of the data's application and authority. The levels indicated the human intervention within the design process. The more complex the data-integration level is, the less human intervention is required, as the human role shifts from being involved in the design itself to being involved in designing and utilising the design tool.

This understanding of the different levels reflected changes of the architecture business process on the microscopic and the macroscopic scale which resulted from adopting a data-driven architectural design process. The microscopic scale resembles the business aspect of the architectural design process, while the macroscopic scale resembles the cultural and social aspects on a wider scale affecting the AEC industry in general.

The Data-Driven Levels led to the development of the Data-Driven Impact on the AEC framework. This framework reflected the emergent business and cultural models by redefining how these data-driven processes affect the design process and identifying the change required to acquire more value through the design process. The framework highlighted the observed value of the following data-driven implementation models: Design, Build, Post-Occupancy, Design-Build, Integrated, and Inter-connected.

This framework aimed to achieve more value in the architectural business by reaching out to data-driven operations as the main components in the design process. The framework highlighted the need for and the means of adjusting current operational models by redefining the roles and the process in the business and the culture. Also, it proposed the emergence of new implementation models and presented the evolution of new roles for architects in the operation process and business.

6.2. Validity

This research followed an inductive strategy adopting a Grounded Theory methodology due to the grounded nature of the data-driven design approach. This methodology was employed in constructing the concepts and the phenomena concerning data-driven operations in a defined context, which is the architecture business.

The validity was demonstrated in the previous chapter (Chapter 5) through applying the established framework to an external case. The research proved valid according to the general criteria for Grounded Theory research proposed by Glaser (1968). The five criteria (Fit, Workable, Relevance, General and Modifiable) were fulfilled.

In addition to this, the proposed framework was verified based on the research assessment of two Grounded Theory criteria: the qualitative criteria Strauss and Corbin's Grounded Theory criteria (1990). Two criteria are used to ensure the reliability of knowledge and the validity of the research; these two criteria are discussed below.

6.2.1. The Qualitative Criteria

The Data-Driven Operational Framework is valid according to the Qualitative Criteria which are based on Credibility, Transferability, Dependability and Confirmability (Lazenbatt and Elliott, 2005). Credibility refers to the accuracy in reflecting the multiple realities of the phenomena (Sikolia et al., 2013). The research's Credibility is established through a continuous engagement with data triangulation, which is achieved using multiple data sources presented in the

variation of the case studies and their domains. Transferability indicates the applicability of one set of findings to another context (Sikolia et al., 2013). Transferability in this research can be clearly realised in the Data-Driven Operational Framework. The generalisation of this framework is transferable into other industries such as product design. Also, the described analysis, the methodology and the interpretation are sufficient to allow another researcher to apply the same analysis in a similar context. Dependability and Confirmability confirm that the data represents the changing conditions of the studies phenomenon (Brown et al., 2002).

6.2.2. Grounded Theory Criteria

The Strauss and Corbin Criteria are based on three sets: The Canon and Procedures of Grounded Theory, the Research Process and the Empirical Grounding of the findings (Corbin and Strauss, 1990).

The research process followed the exact Canon and Procedures of the Grounded Theory set by Corbin and Strauss as the following: the data collection and analysis processes were interconnected from the beginning of the research. The concepts dictated the analysis and formed the core units. The categories were developed and related systematically. The sampling in the Grounded Theory continued on the basis of data-driven phenomenon and the related context. A continuous constant comparison of the cases and the registered processes was completed besides the labelling and the concept-grouping procedure. Patterns, regularities and variations of the analysed cases were investigated and considered. The hypotheses about the relationships among Categories were developed and verified during the research process. Finally, broader structural conditions were analysed reflecting the macroscopic impact of the studied phenomena (data-driven design) that goes beyond the business to cover cultural and social changes.

6.3. Main Contributions of the Research

The research contributes to the emerging knowledge of the concepts of *Big Data* and the *Internet of Things* within architecture. It contributes to the knowledge of data integration in architectural design and business focusing on pushing the industry boundaries to embrace the use of data by adopting data-driven business models and

utilising advanced data technologies as fundamental activities of the design and business process. The following are the theoretical and applicable contributions of the research:

- The introduction of the Digital Value as part of the existing value taxonomy within the built environment.
- Development of a Data-Driven Operational Framework and conceptual modelling of the associated knowledge – a framework that represents the main phenomenon studied.
- Development of a Data-Driven Levels in architectural operations framework – a set of levels that specifies the advancement degree in the utilisation of data in the design process.
- Development of a Data-Driven Impact on the AEC framework – a framework that indicates the impact of data on the AEC current adopted cultural and business models.

6.3.1. General Contribution to Design Practice

The research was carried out with the intention of framing the utilisation of data in architectural design to allow practitioners to develop a viable Data-Driven Operational model. The research and the proposed framework demonstrate the concepts, the context, the process and the value of data-driven approaches and introduce this comprehensive knowledge to the field.

The Data-Driven Operational Framework identifies the operations and the components for employing data in design. This is a developed framework that expands the work of Hatmann et al. (2014) and contextualises the operational data-driven models to be used in Architecture.

The construct of this framework through the analysis of the case studies provide a practical approach than answers Khemlani (2016) questions about the practicality of the research conducted by Deautch (2016).

The "Data-Driven Operational Levels Framework" allows practitioners to reflect on where they stand regarding data integration in their business. This framework

determines the level of data automation employed in the design operations. It expands the work of Vähä et al. (2013) and Balaguer et al. (2008)

The "Data-Driven Impact Framework" provides a thorough insight into the required changes in current cultural and business models. This understanding allows architects to measure themselves and translate this measurement into actions to maximise the acquired value. The anticipated framework exposes the future trends of Big Data for design with data in practice which is proposed by Bilal et al. (2016), Chen et al. (2015) and Volk et al. (2014)

In addition to the recommendation that the research is contributing to the business of architecture, it is also contributing to the broad discussion of data integration culture. While these recommendations are specific to the built environment industry, they also apply to other design industries such as product design.

6.3.2. General Contribution to Design Research

The research contributes to computational design theory and application in architecture.

The research aims to contribute to the existing research in the fields of data integration and management in the AEC industry and architectural design and business. Also, it contributes to the research on architectural value and value creation in general. The research added to the existing values proposed by MacMillan (2006), Mulgan, G. (2006) and Saxon (2005). The advancement is through the proposal of the Digital Value as a driver for other values and the assessment of this Value through the Digital Value Equaliser.

In this research, the concepts of *Big Data* and the *Internet of Things* are examined from an architectural design and business perspective with emphasis on value creation in the built environment. A data-driven architectural design approach is proposed as a business model and a method of acquiring more values in the built environment. The implied research methodology of linking Value, Technology and Business is anticipated to provide an original approach for multifaceted

architectural research which concentrates on the architectural practice and the process.

It is anticipated that the research methodologies and adopted strategies will set a comprehensive example for researchers and scholars regarding the use of the competencies of the Grounded Theory applications in digital architectural design research knowledge. The methodology and the associated methods are transferable and applicable to other research. This add to the work of Birks and Mills (2015) for employing Grounded Theory in practical cases.

The research output of “Data-Driven Operational Levels in Architecture” is anticipated to set a criterion to allocate the scope of future data integrations research, as the identified levels set a wide spectrum for where these data technologies operate.

The research generated a grounded understanding of the changes associated with the implementation of data-driven models in architecture and affects the current models.

6.3.3. General Contribution to Design Education

The research does not have direct impact on design education. However, it reveals the necessity, the benefits and the value of employing profound data technologies in architecture design and business. This employment of data technologies is an extension and a transcendence of the current understanding and modelling of the architecture and design business, and this proposes changes in the profession. Such changes will have an effect on architectural education and the required knowledge and skills. Understanding the fundamental framework of data-driven design and the impact it has is the first step for a change to happen in design education.

While the research does not directly recommend the changes that need to be implemented in the existing design education, it highlights two problems in the current architectural curriculum. The first is the absence of specified business education as architecture students are not educated or trained to run a business on their own once they complete their course (Baillieu, 2013). The second is the

absence of sufficient digital technological understanding with regard to architectural process, management, and information systems, as the majority of architectural education courses focus on the development of the artefact, ‘the building’, rather than on the development of the digital instrumentation of the design process itself (Bernstein, 2017). The first problem was not assessed in this thesis. However, the second problem issues can be tackled by providing a grounded understanding of theoretical and applicable knowledge of values and technologies which contribute to the architectural artefact. This research provides a foundation of this theoretical knowledge. The research findings can be delivered as a module that is comprised of a series of lectures and supported by applied exercises relating to such technologies.

6.4. Recommendations for Future Work

The research opens opportunities for future work in the field of data integration in architecture design and business.

The research provided the theoretical understanding of the process of implementing a data-driven operational mode in architecture and the value of such an approach. It provided a sound basis for experimental research that is stimulated from the established theoretical framework. An empirical work of applications will provide better assessment and validation for the proposed research and a framework.

With regard to the different identified levels of data-driven operations, it is recommended to design a case from the acquired knowledge and to develop the case design process incrementally, starting from Level 0 and moving up. In this recommendation, the proposed case provides a controlled context which offers a clearer understanding of the change in the process due to the possibility of controlling variables.

Identified methods of data-driven architectural processes from the completed case studies set an opportunity to research and expand their use in further applications beyond the case scope. Each case study was analysed thoroughly, and a recommendation was given to enhance and improve the process; these recommendations set proposals for future work. An example of this is the concept of Voxelisation and the given recommendation of providing meta-data as part of the voxels^o, which allows further utilisation of data. Another example is expanding the research on the implementation of kinetic architectural elements in the context of the business. This implementation provides an opportunity to adopt a new process and fee system.

One possible future study is to develop a value assessment tool for the architecture business which is based on the acquired knowledge of the proposed framework. This tool is represented by a computer software program and a graphical user interface which enables value to be assessed based on the input of data types and provides architects with sufficient information about the suggested operational process and business model. To achieve this, a data warehouse needs to be established based on the research framework. This data warehouse will register all

architectural values and associated business processes based on the provided components. The tool will have a query feature to allow architects to interact with this data based on the required achievable value.

Although the research is concerned with the concepts of *Big Data* and the *Internet of Things*, it is not limited to them. One of the existing AEC applications that provides an opportunity to investigate these data-driven business models is BIM (Building information Modelling), which has been implemented in the industry on different levels. The information in the BIM model has become more important than the modelling itself, as information is variable and provides more insights than the Geometrical Data itself. However, the current levels of BIM do not allow the implementation of external un-aggregated data. Implementing Data-Driven techniques in BIM has the potential to empower it and to expand its values. A study regarding implementing a Big Building Information Management approach is recommended.

The research sets a starting point and provides all the required knowledge to proceed with the previous recommendation.

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Appendix 0: Case Studies Lists

The following table shows the list of case studies that have been considered for the case studies analysis:

Case Study Title	Description	Reference	Link
City Dashboard	Dashboard that represent spatial data for cities around the United Kingdom		http://citydashboard.org/london/
City Beats	Visualising the social media trends of the city utilising	(Xia et al., 2014)	http://thecitybeat.org/
Fluidity	Interactive Art Installation	(Ronchi and Benghi, 2014)	http://www.aether-hemera.com/Blog/2013/7/30?Id=Fluidity%40Northern_Design_Festival_2013
The applicability of BIM in geospatial environment	Site selection and fire response management utilising BIM and GIS	(Isikdag et al., 2008)	
BIM- for supporting indoor navigation requirements	A BIM approach to develop an indoor data model	(Isikdag et al., 2013)	
A cloud approach to unified lifecycle data management in AEC	Integration of project management data utilising business social networking services	(Jiao et al., 2013)	
Project Dreamcatcher	A generative design tool that allows designers to generate solutions based on		https://autodeskresearch.com/projects/dreamcatcher

	defined goals and constraints		
Automated daily pattern filtering of measured building performance data	A data mining process for daily building performance data	(Miller et al., 2015)	
Nick Savko and Sons	Using Telematics in the CSX Railroad trans-shipping terminal project	(Sprouls, 2010).	
BIM and RFID Integration: A Pilot Study	Integrating BIM and RFID technology during the operation and maintenance	(Meadati et al., 2010)	

Appendix 1: Case Studies Coding

This section presents snapshots of the coding process of all the discussed case studies in this thesis. The figures and tables are amended for clearer presentation.

Case Study 1

Data Offering iNSIGHT set out to explore the possibilities of exploiting shopper movement analytics across a high street to enhance consumer profiling and, based on this profiling, to provide individual consumers with a personalised shopper experience. To explore the potential of doing this, Red Ninja subcontracted the University of Liverpool Electrical Engineering & Electronics faculty. Although it was recognised that an extended sensor network would provide more data to exploit, the core sensor network deployed to run a trial as part of iNSIGHT proved that the sensor technology has the capability to provide desired information on footfall, visitor duration and return consumers.

Key Activity Although the data generated through the deployed Location-Based Sensor Network is anonymous and no personal or sensitive data is collected, Red Ninja has collaborated with the Digital Catapult to conduct a high level gap analysis on the present methods and systems used by Red Ninja to collect and process data. Based on this, the Catapult provided a roadmap towards a model of best practice that will in due course lead to a data privacy best practice framework which is in line with both national, European and international data privacy regulations and guidelines. Avoiding any risk that could potentially lead to privacy infringements, this collaborative work has proved to be very effective and ensures the right framework is in place for further testing and deployment in Phase 2.

Value Proposition • Liverpool One iNSIGHT: a consumer analytics dashboard for retailers, which allows shopping centre managers and / or BID teams to gain an enhanced consumer insight. The key added value of this dashboard is that it provides retailers, shopping centre managers and BID teams with real-time data about visitor flow, footfall timeline, average zone popularity and average visitor duration across their high street. At present, no such information is available to the Liverpool high street. Besides the ability to enhance consumer profiling based on their movement and their shop visit pattern, iNSIGHT enables these stakeholders to optimise their infrastructure and justify marketing spend. To clarify, Liverpool One's management team spends a significant budget in particular zones of its shopping centre to optimise visitor duration and footfall. However, as there is no effective method to prove that this marketing spend has the desired effect, it is difficult to justify this spend. As a result, this dashboard equips retailers, shopping centre managers and BID teams with a tool that gives them new and reliable data about what they care most: footfall, visitor flow, zone popularity and visitor duration.

As described earlier, our vision for the UK high street is based around the following pillars:

- Value Proposition** 1. A consumer super-app that help shoppers to plan and navigate all stages of their journey; be rewarded for loyalty, experimentation, dwell time and spend; and build a more personal relationship with their local high street. Plus a retailer insight dashboard that delivers valuable insight into consumer behaviour, and supports targeted marketing campaigns and spend, attracting users back to the high street.
- Value Proposition** 2. A cost-effective and high accuracy Location-Based Sensor Network that tracks people movement data in key shopping locations and the wider geography.
- Data Offering** 3. New uses of data that deliver consumer profiles based on people movement data.
- Value / Economic** 4. The development of a UK Retail Data Privacy Framework that builds trust amongst consumers and enables retailers to adopt best practice.

Figure 86 Open Coding Process of Case Study 1 on Text

Table 61 Key Codes of Case Study 1

Open Codes	Words from texts		Axial Codes
Data Source	Sensors detecting pedestrian movements 3D Model of Liverpool ONE		
Data Offering	High Accuracy Location-Based tracking. Shopper Movement. Real-Time Data. Analytics. Footfall Timeline (2) Visitor Duration. (2) Return Consumers information. Visitor Flow. Zone Popularity. Consumer Behaviour. Insight (3)		Input - Technique Output – Information Input Analytics Output – Information Output – Information
Data Handling	Extending the Sensors Network. Data Generation through Location Based. Collect. Process. Generate New Data.	Privacy	Generation Collection Processing Generation
Value	Use	Enhance Consumer Profiling (2) Personalised Shopping Experience. Optimise infrastructure. Justify marketing spend.	
	Economic	Cost Effective	
Value Proposition	Analytics Dashboard (2) Consumer Super-App		Application – Dashboard Application – Mobile App

Case Study 2

* * About This Project *

Architectural Value Proposition
Data Offering
Key activity

The **Chicago Energy Data Map** is a visualization of all residential natural gas and electric energy use — both by neighborhood and by census block — for the City of Chicago in 2010. The height of each neighborhood or census block indicates electric energy consumption while the color is indicative of natural gas consumption.

Data Offering
Data Offering

The purpose of this visualization is to allow the viewer both a bird's eye view, as well as a neighborhood detail view, of energy consumption patterns in one of our nation's largest cities. Further, users can review energy efficiency tips and Chicagoans can pledge to make improvements to the efficiency of their homes on behalf of their respective neighborhoods.

Architectural Value - Use
Architectural Value - Use
Architectural Value - Social

This project is a collaborative effort between the **City of Chicago**, the **Civic Consulting Alliance**, **Datascope Analytics** and **IDEO** with support from **Accenture**, **Elevate Energy**, the **Citizens Utility Board**, **ComEd** and **Peoples Gas**. The Chicago Energy Data Map is part of **Mayor Rahm Emanuel's** Retrofit Chicago initiative.



Key activity

Note: All data was analyzed at the census block and neighborhood level to protect the privacy of Chicago residents.

* * * *

Architectural Value - Psychological

* *

EASY TIPS TO HELP YOU IMPROVE ENERGY EFFICIENCY IN YOUR HOME

* *



Architectural Value - Economic

Your annual cost savings will increase with every tip you pledge to try out!

Filter tips by type of home: Single Family Home

Architectural Value - Economic

1. Use advanced power strips for plugs \$27

I'LL DO THIS!

EST. ANNUAL COST SAVINGS

\$0

2. Use a ceiling fan, not the AC \$225

I'LL DO THIS!

3. Turn off coffee maker after brewing \$30

I'LL DO THIS!

More tips

Confirm your neighborhood so we can add your pledge to the leaderboard!*

*You will be asked to log in via your preferred social means

 ENTER YOUR NEIGHBORHOOD

* * * *

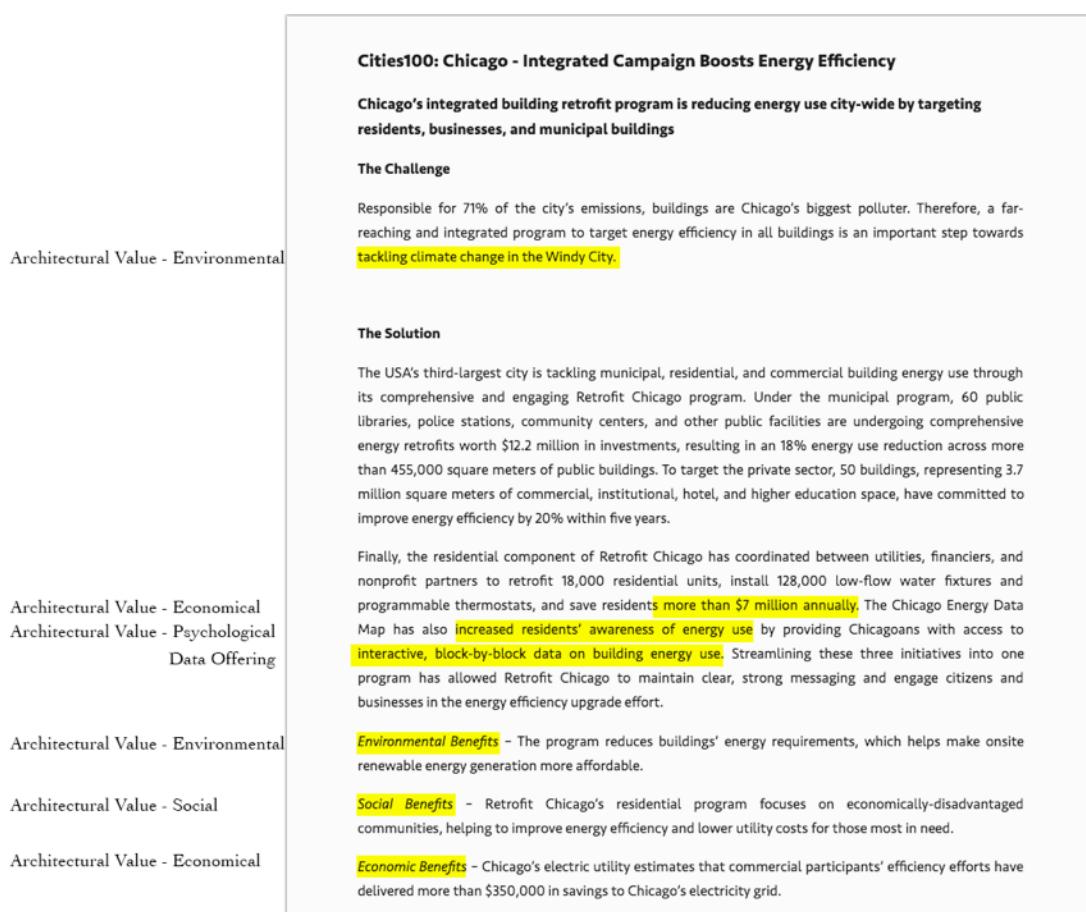


Figure 87 Open Coding Process of Case Study 2 on Text

Table 62 Key Codes of Case Study 2

Open Codes	Words from text		Axial Codes
Data Source	Geographical data 3D Geometric Data Energy Use Data		Static External Static External Active External
Data Offering	Energy Use (2)		Output - Information
Data Handling	Data Analysis Data Visualising	Privacy	Analysis Modelling
Value	Use	Increase Home Efficiency	Application
	Social	Neighbourhood Efficiency Retrofitting the City Program	Output - Information
	Economical	Saving Money (2)	
	Environmental	Reduce Building Energy Requirements Increase Energy Efficiency	
	Psychological	Increase Awareness Collective Behaviour-modification	

Value Proposition	Visualisation Interactive Interface		Visualisation Interface
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Case Study 3

scales; while the second build and run models of landscape dynamics, combining event simulation with a spatial database. Smart Plan developed by Sasaki [5], focuses on the intermediate landscape scale, including building use in their interactive models. Software companies such as Autodesk [6] with DreamScape by 3DS Max, focused on rendering realistic landscapes, LANDCADD, Eagle point, and Land F/X, on the design of irrigation systems. Also, plug-ins such as Carbon Scatter (by 3DS Max) helps designers to manage populations, such as large distribution of trees. KeyPAVING and Siteworks [6] are grading tools to model pads, parking lots, streets, sidewalks and more. Vectorworks Landmark [7] allows to set trees, sun, site buildings, as well as plant lists, importing PDFs and DWGs. Landmark also allows export formats such as images and databases, as well as 2D and 3D representations. Also, there are some efforts on interaction using large screen maps [8, 10], negotiation of stakeholders using virtual reality and physical interaction for terrain manipulation [9].

Our proposal is that Campus Information and Knowledge Modeling integrates both building and geographic scales into a campus scale model [11]. CIKM stores information about spatial as well as non-spatial features, comprehensively analyzes spatial and non-spatial data, such as cost and goals, to finally integrate the spatiotemporal-referenced information, by scenario structure, displaying it as a spatial and temporal representations. Georgia Tech's CIKM is composed of building and landscape information combined into one design space [12,13]. However, independent of the technological improvements that could be applied to our project, our main goal is to integrate information and knowledge, and propose a method to capture specific expert knowledge from landscape designers, and include it in the process of design and implementation of the CIM tool. The main objective of this method is to construct the knowledge taxonomy by Knowledge Type, Strategies, and Structures (table 1), which can be stored and accessed digitally.

2. AN INTERACTIVE TABLETOP FOR LANDSCAPE DESIGN

Campus Landscape information Modeling –CLIM tool– was developed with the purpose of supporting direct collaboration among different disciplines by accessing real time information and evaluating landscape projects [14, 15]. The main structure of the model allows storage and retrieval of alternative designs as projects or scenarios. A project is defined by three variables: the area to be modified, the initial date, and duration of the project in a timeline. It could be stored by name, and has a list of goals and constraints, classified by owner. For example, a parking building's owner is *Parking and Transportation Services*, which has their own budget and managers. However, the parking serves the Student Center.

Key Activity

Architectural Value / Display

Data offering / Collaboration

Key Activity / Storage, Retrieval

Data Sources / Variables

Scenario is a collection of projects, which may have different clients or stakeholders, but which collectively have specific goals, locations, or scheduling in common. For example, a tennis fields on top of a parking structure. They are part of the same physical project, yet support global goal: Increasing the amount of green spaces in core areas of campus. Budgets, however, come from different departments, and have different interests, goals and constraints. By taking advantage of the data storage system, we proposed a scenario comparison toolkit to find the best alternative.

3. CMIK: CAMPUS MODELING OF INFORMATION AND KNOWLEDGE

Data Source	CMIK's two fundamental models –information and knowledge models– differentiate themselves by the complexity of their construction. While the information model refers to the integration of geometric representation of objects and their attributes, the knowledge model refers to the variables, constraints, goals, operations, and their relationships to construct quantitative and qualitative evaluations, in order to specify semantic meanings. These two models organize frameworks for data and knowledge, for exploration and understanding of decisions, and for comparison across systems. The top-view of the campus, which is displayed on the tabletop, is constructed on top of two types of information model views: A raster model representation and a vector representation (see figure 1). Raster models represent land use types, while vector models represent land elements such as trees from the tree inventory carried out in 2012 and are continually updated. Assessment results, which are visualized on the dashboard, integrate literal information and the expert knowledge from sources, to convey the relationships, dependencies, and conditionals for decision-making. The user interface features –such as the layout, icons, and commands– are constructed on top of the aforementioned information models and knowledge model. In the following section, we describe in detail the information models and the knowledge models on which our CLIM is built.
Data Source / Data Types	
Geometry	
Architectural Value / Dashboard	
Architectural Value / Interface	
Key Activity	
Key Activity / Translate	
Key Activity / Translate	
Data Source	
Data Source	

technological and human resources, firstly to collect it and store it, constructing an “organizational memory”, for communication among users and reuse in context [20]. For several decades, the focus of Knowledge-based system Engineering has been on the development of methodological approaches to operationalize experts’ knowledge, developing appropriate methods, languages and tools for Knowledge-based systems (KBS) [21, 22]. This organizational memory is a combination of unstructured and structured knowledge of diverse sources.

5. KNOWLEDGE SOURCES

Data Source / Information

Campus Information-and-knowledge Modeling (CIKM) was conceived for a specific university campus: the Georgia Tech campus. Both general and specific sources of information and knowledge were utilized to construct these two fundamental models upon which CIKM is based.

Data Source / Knowledge

The information model is based on raw data, such as land use, tree inventory, parking

Key Activity / Elicitation

inventory, lighting inventory, water systems, etc, that was extracted from global and local written sources as well as specific samples.

The knowledge model is constructed from expert and user knowledge, which was extracted from both written and non-written sources.

For the latest, we used four elicitation techniques to gather knowledge: Existing documentation, Observation of experts collaborating on a specific case study, analysis of tasks of the specific case study, and interviews with experts and users [23].

Written sources and elicitation techniques

Data Source

Manual , FICM, Master Plan, Vision, Plan

We used five main sources to extract expert knowledge about campus design. The basal knowledge came from a manual about educational facilities

Key Activity

in general, FICM Manual, and then from Campus Master Plan and Strategic

Key Activity

Vision and Plan documents, which are specific to the campus. Once the documents were processed and the knowledge was classified, we continued

including experts perspective form a City Planning Studio. Intermittently, we ran our project structure through a specific and real-world case for a

campus renovation for 2015, lead by the Space and Management group.

From the Campus Master Plan and Strategic Vision documents we recognized the main goals and constructed a principal causal model. This model helped us to understand what variables influence the accomplishment of main goals and secondary objectives. As we will review, these goals are both quantitative and qualitative; therefore we developed a strategy to include them on our causal model. We verified the model through reviews

Key Activity

with planning and design experts.

structure of the knowledge dimension of the Bloom's revised taxonomy of Factual, Conceptual, Procedural, and Meta-Cognitive Knowledge [25] as a base for the structure of our knowledge-based model, using four strategies respectively: Specifications of Details; Categories, Models, and Structures; Algorithms and Procedures; and Strategies (table 1) [13].

Knowledge Dimension	Knowledge Strategies	Knowledge Structure	Example	Knowledge Source
Factual knowledge	Terminology and Specifications of Details	<ul style="list-style-type: none"> - Elements representation - Colors - Modified Information 	<ul style="list-style-type: none"> - Tree Type - Tree location - Land Use 	FCIM Case Study
Conceptual knowledge	Categories, Models, and Structures	<ul style="list-style-type: none"> - Categories Structure - Groups of Categories - Layers - Timeline 	<ul style="list-style-type: none"> - Layen - Zones - Projects - Scenarios 	FCIM Case Study
Procedural knowledge	Algorithms and Procedures	<ul style="list-style-type: none"> - Commands - Variables - Constraints - Evaluations - Assessments - Design Guidelines 	<ul style="list-style-type: none"> - Remove Tree - Change Land Use - % Area - Based on Budget - Parametric sections - Evaluations 	FICM CMPU Interviews Case Study
Meta-cognitive knowledge	Design strategies Context and Conditions	<ul style="list-style-type: none"> - UML Structure - Layout - UI Design 	<ul style="list-style-type: none"> - Time representation - Scenarios - Goals - Structures - Strategies 	Case Study Interviews CMPU

6.1 Factual Knowledge

Factual Knowledge refers to the basic elements within a discipline [25]. It emerges from the combination of raw information and expert knowledge that modifies that information by specifying graphic representations, such as colors and representation of elements. For example, the raster model is based on land use information extracted from pure data, however, how it is classified into twenty nine hierarchical land use types is defined by the FICM manual [16]. Also, the colors used to visually represent land-use types in our model are the colors proposed on the CMPU manual [17]. Mapping the information from the tree database, such as tree location or tree canopy, to vector-point information is a literal visual representation from data to icons, but the tree typology we use is defined by the CMPU manual.

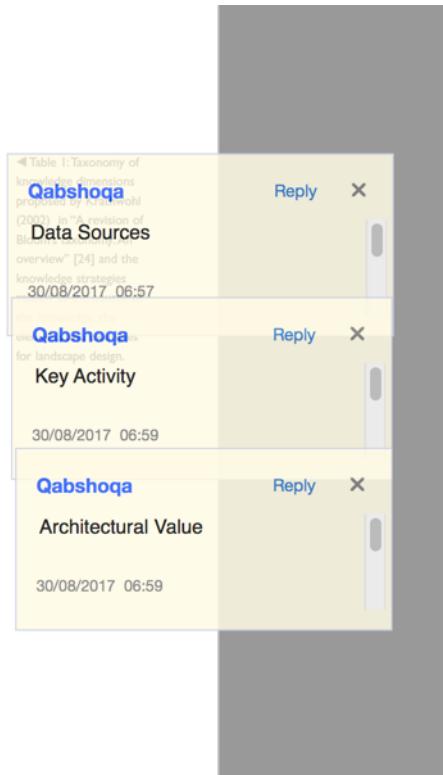


Figure 88 Open Coding Process of Case Study 3 on Text

Table 63 Key Codes of Case Study 3

Open Codes	Codes from Text			Axial Codes
Data Source	Information Models	Integration of Geometric Representation of objects and their attributes	Raster. Vector.	Input - Geometry
	Knowledge Models	The variable Constrains Goals Operations		Input - Parameters
	FICM Landscape Master Plan Planning Studio Interviews Case Study			Input
Data Offering	Support Collaboration. Storage and Retrieval of Alternative Design or Scenarios. Display Spatial and Temporal Representation			Application Intervention Application - Interface
Data Handling	Integrates BIM and GIS. Data Analysis. Data Processing. Data Classification. Data Recognition. Data Storage. Data Retrieval, Data Translate.			Analytics Analytics Processing Aggregation Intervention Input Intervention Modelling

	Data Connection.	Analytics
Value Proposition	Dashboard User Interface Design Strategies	Application – Interface Output

Case Study 4

<p>pects, while most of it is built upon stories which describe it and the individuals who transfer the stories or identify with them. Therefore, besides designing an object, it is also necessary to design a narrative which defines its meaning.</p> <p>The research focus of the project <i>Four Chairs and all the others</i> is the design of a chair which does not carry on the heritage of iconic or functional pieces of furniture, but a one which contains information about "all chairs ever created", for which the term <i>Eigenchair</i> is used - to describe a sum of ideas. The algorithm database contains a number of "other chairs". Their fusions enable an infinite variety of possible results. In order to achieve a certain control over the results, out of "all other chairs" we have chosen four chairs as a precondition for creating identity and narrative. Fusions of characteristic parts of these four chairs with all the others are defined by user made maps that define the transformations, by upgrading the performance of the <i>Principal Component Analysis</i> tool, and enable the control of the result (Figure 5). The project <i>Four Chairs and all the others</i> refers to four iconic chairs: Thonet's Chair No.14,</p> <p>Data Offering</p> <p>Key Activity</p> <p>Data Source</p> <p>Key Activity / Merge, Transform</p> <p>Key Activity / Upgrade</p>	<p><i>Wire Chair</i> by Charles and Ray Eames, <i>Panton Chair</i>, and Ghery's <i>Wiggle Side Chair</i> (Vegesack et al., 1996).</p> <p>Their main mutual link is specificity and uniqueness of the material and their respective technological innovation, depending on the context in which they were designed. It is the richness of meaning and historical references of these examples that are responsible for enabling us further creation of analogies, stories and narratives, which, in turn, fertilizes viewer's active participation in the process of visual representation.</p> <p>MULTIDIMENSIONAL VECTOR - TECHNICAL APPROACH</p> <p>The project <i>Four Chairs and all the others</i> deals with manipulating data, thereby generating new objects. A whole library of chairs, that is, their geometric and spatial characteristics, along with their historical importance and their narratives, is taken as the starting point of the project. By using open source 3D models of chairs from Google warehouse, their geometry is appropriated through a set of algorithms, after which the <i>Principal Component Analysis</i> algo-</p> <p>Data Source</p> <p>Key Activity / Manipulation, Generation</p> <p>Data Source / Types Geometric, Historical</p> <p>Data Source / Open 3D</p> <p>Key Activity / Algorithm</p>	
--	--	--

Figure 4
3D printed models of chairs generated by EigenChair application.



Key Activity / Merge, Manipulate

Data Offering

Architectural Value

Key Activity / Normalise

rithm is used to fuse, merge and manipulate input information and create new objects. The result is a population of objects that are over coding cultural and historical space-time relations through logistic networks. Final design is entirely a product of mathematical and logical thinking. The object now becomes a product of pure intellect, grounded in history and culture. The main algorithm, which defines the whole project, is *Principal Component Analysis* algorithm.

Logical steps

The initial step was to normalize and prepare the data of all the chairs. In this case study, 12 chairs

were used as testing data set due to the computational limitations. All data had to fit in the same bounding box, and mesh vertices were equally distributed throughout the mesh. **Key Activity / Aggregation**

The whole application consists of three main parts. The first part is the *Algorithm for Voxelizing Polygon Meshes*. This algorithm transforms each mesh into a voxel based object defined by a one-dimensional numerical array list, i.e. multidimensional vector. In case of the highest resolution, each chair is represented with 2,788,671 values. Each value marks the distance between the given voxel and the closest mesh vertex. Values for each chair are exported as separate txt files, in order to reduce computing time of the main application (Figure 6).

The second part is the *Algorithm for Morphing Chairs*. The base of this algorithm is the *Principal Component Analysis*. The goals of *Principal Component Analysis* are to extract the most important information from the data set; compress the size of the data set by keeping only the important information; simplify the description of the data set; and analyse the structure of the observations and the variables.

<p>Key Activity In order to achieve these goals, <i>Principal Component Analysis</i> computes new variables, called <i>principal components</i> or <i>Eigenvectors</i>, which are obtained as linear combinations of the original variables. The first <i>principal component</i> is required to have the largest possible variance. The second component is computed under the constraint of being orthogonal to the first component and thus having the second largest possible variance. The other components are computed likewise (Figure 7).</p> <p>Key Activity According to the size of the initial bounding box, a voxel-based space is created. Each voxel receives values from txt files exported in the first step. With the use of <i>Principal Component Analysis</i> we can represent each chair by using only a set of <i>Eigenweights</i>, e.g. (-5673, -85184, 50, -25533, 31594). By changing the values of <i>principle components</i>, i.e. <i>Eigenweights</i>, we are able to achieve linear transformations between all the chairs (Figure 8).</p> <p>Key Activity The third part is the <i>Algorithm for Mapped Morphing</i>. It is an upgrade from linear <i>Principal Component Analysis</i> transformation to a nonlinear mapped transformation. An RGB map, in which each color represents a particular chair, is projected to the voxel-based space. This enables us to define and control the nonlinear transformations and fusions of three different chairs into a new one. Thus created, chairs can be used again as input chairs for the second step, and achieve a new nonlinear variability (Figure 9).</p> <p>The rest of the algorithms served to prepare the data for <i>Principal Component Analysis</i> and to help with their final visualization. An important role was also played by a series of open source libraries, especially the <i>Marching Cubes Algorithm</i> (Lorensen and Cline, 1987), responsible for generating watertight mesh objects ready for 3D printing. All codes were written in Java programming language.</p> <p>Key Activity / Recycling Having in mind referential and recycling discourse, it is important to note that the algorithms used in the project, e.g. <i>Principal Component Analysis algorithm</i> and <i>Marching Cubes Algorithm</i>, are already in practice. They are thoroughly adapted and functionally redirected, recycled to fit the needs of design.</p>
ARTICULATING INDEXES - THEORETICAL APPROACH

Figure 89 Open Coding Process of Case Study 4 on Text

Table 64 Key Codes of Case Study 4

Open Codes	Codes from text		Axial Codes
Data Source	Existing Designs	Thonet's Chair Wire Chair Panton Chair Ghery's Wiggle Side Chair	Input – Geometry Aggregation
	Open 3D Library	Geometry	Input - Geometry
Data Offering	Design Genealogy Sum of Ideas Infinite Varieties	Objects over coding cultural and historical space-time relations	Intervention Output Output
Data Handling	Data Fusion Mapping Transformations (2) Analysis Manipulation Merging Generation Normalise Data Applying Algorithm (3) Computing Recycling	Voxelisation Morphing Mapped Morphing	Intervention Analytics Modelling Analytics Analytics Analytics Output Processing Analytics Processing Processing Processing
Value	Image	Create New Design	Output
	Cultural	Create analogies Create Stories Create Narratives	Output
	Psychological	Fertilize viewer's active participation	Intervention
Value Proposition	Generate New Designs		Output

Case Study 5

	University College London (UCL). Grounded in thorough and rigorous research of both a client's organisation and its space, the process provides new levels of insight into the social and spatial functioning of a business.	study of occupancy, movement and interaction brings to light how people actually use the space. These methods are combined with spatial analysis techniques using DepthMap software, ³⁶ which assesses the performance of the workplace layout revealing the potential of space to integrate or segregate people, and thus how it facilitates collaboration.	Data Source Key Activity / Analysis Key Activity
Key Activity	The process often starts by working with senior management to establish a clear understanding of the issues and challenges currently faced by the organisation, and to set the overall measurable benefits to be delivered by the project. Often clients do not know exactly what they need from a space; at the same time, not many companies are actively collecting performance metrics themselves. Essentially, the first step of the approach is to create a more informed and systematic brief for the project. A series of structured one-on-one 'stakeholder' or head of department interviews then helps to clarify the current and desired future working practices of different parts of the organisation as well as informing an understanding of the interaction and collaboration networks in the business. An online staff survey is used to explore what individuals need from their work environment, how satisfied they are and how well they perceive it currently matches up to the task. Last but not least, an observation	Through the layering of this evidence, and in conjunction with the client, strategic recommendations are made for an ideal space, and new ways of working within it. A spatial strategy is then developed that includes a schedule of total recommended space requirements, as well as a masterplan (see Figure 1), which maps key spatial relationships between departments. These provide an extensive and detailed brief that:	Data Handling / Combining Business Channel Architectural Value / Use Business Channel
Data Offering		<ul style="list-style-type: none"> defines the fundamental principles of a workplace design that is tailored to the exact needs of an organisation; allows an organisation to change (if desired); and increases the satisfaction, happiness and wellbeing of employees. 	Architectural Value / Strategy Architectural Value Architectural Value / Image Architectural Value / Use, Psychological
Data Offering			
Data Source			
Architectural Value			
Architectural Value			
Data Offering	This strategy and masterplan can be used to either compare options in a property search and inform future design stages within a new property, or reveal how to make an existing space work better for its inhabitants.	without the need to compromise the performance of the workspace itself. Often it has been possible to reduce space while in fact, at the same time, enhancing spatial and hence business performance.	
Value Proposition			
Value Proposition			
Data Offering	Creating a structured brief in this way has two obvious advantages: first, it creates long-term value. The spatial design of a workplace is a big investment and, by following a data-driven approach, the chance of 'getting it right' is significantly increased. Thus the short-term upfront investment (in time, money and effort) of data-driven design is justified easily by the long-term gains.	In a recent project example, a London law firm was looking for ways of releasing a minimum of 2,800m ² of space. Using a range of data gathering and analysis techniques it was possible to demonstrate a potential saving of 7,250m ² , which represented a 32 per cent space saving on its total London property portfolio, and yet also included some additional facilities that were not currently available to legal and support staff. An accommodation analysis comparing space allocation to benchmarks for equivalent organisations showed savings were possible in storage and primary circulation; there was also the potential that moving from cellular to open-plan workspace would provide. An observation study established that, contrary to perception, actual desk occupancy levels were on average 44 per cent, including in the cellular accommodation, and also showed how little communication was happening on a day-to-day basis between different specialist legal teams. Head of department interviews and an online survey helped to establish the activities that people needed to be engaged in to get their job done, and the bigger strategic issues that the firm was facing. They also highlighted that the current inefficient layout lacked important facilities such as designated multidisciplinary project rooms. The result was the client was able to plan to vacate an entire building that had the additional benefit of bringing the whole firm together in one place, leveraging the possibilities of greater cross-disciplinary working while delivering significant cost benefits over and above the investment.	Key Activity Key Activity
Value Proposition			
Business Benefits			
Business Benefits			
Key Activity			Data Source
			Data Source
Architectural Value	HOW CAN WE FIT MORE PEOPLE IN?		Architectural Value / Use
Architectural Value	Cost saving is always on the agenda of any business. Reducing the total area that the business occupies is an easy target for cutting operating costs; however, this is often in the context of the size of the organisation staying the same or even growing. Faced with this challenge, the easy and conventional approach is to add in more desks at the expense of other facilities, such as break-out areas, which are often seen as 'nice to have'. The data-driven approach, in contrast, is to gather evidence about the way the business actually needs to work and how well the space currently performs against that. This means that a detailed accommodation schedule of requirements can be calculated from the bottom up. In this way it is possible to quantify potential space savings.	DOES EVERYONE NEED A DESK?	Business Benefits
		Advances in technology and the rise of knowledge work have transformed people's	

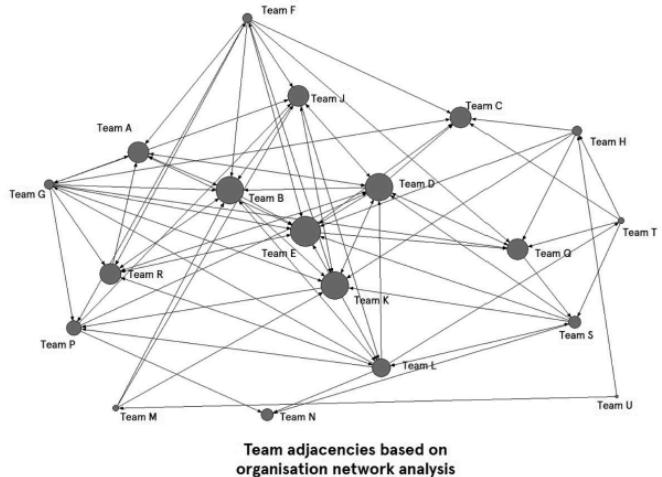


Figure 3 The organisational network of desired future collaboration patterns (based on interviews with heads of department) at a Manchester-based advertising agency

the CEO. But an alternative approach was taken in this case: investing time up-front to carry out a detailed requirements-gathering study. This included collecting evidence about the way in which staff were occupying their existing space and surveying them about their future business requirements, including modelling current and desired collaboration patterns between departments.

Data Handling
Data Source
Key Activity
Key Activity / Modelling

Data Offering
 Using the data to establish a set of strategic design guidelines, such as adopting consistent workspace densities and moving from departmental meeting rooms to a centralised shared facility strategy, the company was able to draw up a list of measurable spatial criteria that formed part of the property search brief.

Each shortlisted property not only could be assessed against these criteria, but also could be analysed in terms of its spatial configuration and potential to integrate or segregate people. Figure 4 illustrates an example of comparing

the spatial potential of two different properties. Both options showed similar overall levels of integration, yet Option 1 provided higher levels of rather integrated space, whereas Option 2 showed a higher range of variation of spaces from integrated (suitable for collaboration) to segregated (suitable for concentration). The link between the two wings of Option 2, however, is rather narrow, which means a natural tendency of the floor plan to split an organisation into two parts. This information allowed the client to make an informed decision (which in this particular case was to reject both properties and look for another, more suitable, one). Therefore, the spatial layout of a potentially interesting property became another layer of information to guide the final selection process. The company has since successfully relocated. The new interior design — based on the strategic guidelines that were

Data Offering
Business

Figure 90 Open Coding Process of Case Study 5 on Text

Table 65 Key Codes of Case Study 5

Open Codes	Codes from Text	Axial Codes
Data Source	Occupant Survey Observations Study (2) Occupancy Study Movement Study Interaction Study Interviews (2)	Input / Collection Input / Collection Input / Collection Input / Collection Input
Data Offering	Measurable Benefits and Criteria (2) Systematic Brief (2) Reveals Interaction and Collaboration Network Informed Decisions	Output - Information Output Output - Interface Intervention
Data Handling	Establish an Understanding Structured Interview and Surveys (2) Spatial Analysis (DepthMap) Data Layering Communication Gathering and Collection (3)	Processing Collection Analytics / Modelling Analytics Modelling Gathering

	Analysis (2) Modelling		Analytics Modelling
Value	Use	Staff Needs Ideal Space (2) Fundamental Design Principal Evacuation	Intervention - human Intervention - human Output Application
	Social	Potential of Space Integration or Segregation (2)	Output
	Image	Organisation Image	Output
	Psychological	Occupant Satisfaction (2) Occupant Happiness Occupant Wellbeing	Output
Value Proposition	Generate New Designs Compare Designs Inform Future Designs Enhance Space Long Term Value		Output / Intervention - Automated / Modelling Intervention - CAE Intervention - CAE Intervention - CAE
Business	Strategic Recommendation Spatial Strategy (2)		Intervention – Human Output

Case Study 6

ABSTRACT

Public displays and projections are becoming increasingly available in various informal urban settings. However, their potential impact on informing and engaging citizens on relevant issues has still been largely unexplored. In this paper, we show that visualizations displayed in public settings are able to increase social awareness and discourse by exposing underlying patterns in data that is submitted by citizens. We thus introduce the design and evaluation of *Reveal-it!*, a public, interactive projection that facilitates the comparison of the energy consumptions of individuals and communities. Our in-the-wild deployment in three distinct physical locations provided insights into: 1) how people responded to this form of display in different contexts; 2) how it influenced people's perception and discussion of individual and communal data; and 3) the implications for a public visualization as a tool for increasing awareness and discourse. We conclude by discussing emerging participant behaviors, as well as some challenges involved in facilitating a socially motivated crowd-sourced visualization in the public context.

Author Keywords

public display; urban screen; urban visualization; energy consumption; sustainability; in-the-wild study; awareness, reflection; captology; persuasive computing; evaluation.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: Miscellaneous

INTRODUCTION

Electronic displays are becoming increasingly ubiquitous in our urban environment, ranging from community centers, museums to airports. As display technology is developing rapidly, it is likely that this trend will accelerate, so that people will become more accustomed to this type of situated media [19, 41]. With their visual presence and

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opportunistic accessibility, such urban displays form promising communication platforms for citizens [9, 14, 23, 41]. While the majority of urban displays serve mainly civic, commercial, artistic or entertainment purposes, only few works present a civic goal: that of increasing the awareness and discourse on socially relevant topics [1, 38].

One topic of growing public concern is environmental sustainability. Several non-governmental organizations are actively trying to raise awareness on this issue by focusing on making relevant data available in the public media. However, although people are becoming increasingly conscious of the ongoing "Climate Crisis", they are rarely aware of how their own activities contribute to greenhouse gas emissions [24, 36]. As a result, the interaction with energy-consuming appliances tends to occur without any conscious consideration of their environmental impact [33]. Recent initiatives address this problem by providing tools for precise quantitative measures of energy or monetary expenditures. Confined in a private context, these tools negate the potential of social comparison [15] and discussion, which might support people in making sense of, and reflecting on, their personal consumption habits. Furthermore, they tend to not gracefully integrate into the physical environment, and do not typically spark occupants' curiosity [47].

We propose that these opportunities could be addressed by exploiting the unique characteristics of social visualization within the context of the urban environment. Social visualization, in its original definition, describes the enriching of social, electronic communication by making its rich and salient qualities visible in easily accessible and understandable ways [12]. Accordingly, social data exploration offers people the chance to increase their understanding of complex information by the power of collective and collaborative efforts [51]. Recent research in this field has indicated that people seem to become encouraged to create public visualizations for participative purposes, even spurring social activities alongside [11, 17]. While most social visualizations have focused on online environments, little is known on whether they can be successfully deployed in other contexts, such as public spaces. Accordingly, we hypothesize that awareness and discourse about citizen-related issues may benefit from the

Business

Value /
Social

Design Workshop

We conducted an iterative refinement of design constraints and requirements during a collaborative 3-week workshop with data visualization experts [47]. This process was conducted in an extensive dialogue with paper and digital sketches, interactive prototypes and tests in-the-wild.

Based on the design activities and previous work, we set out to build an urban visualization display that would a) provide awareness on individual and communal data but consider privacy; b) promote socially valid comparisons; c) encourage opportunistic and spontaneous conversations; d) be understandable and enjoyable; and e) be accessible and aesthetically-integrated in the physical environment.

THE URBAN VISUALIZATION DISPLAY “REVEAL-IT!”

Key Activity To structure and maintain an overview of the design goals, we used the Design Space Explorer Framework for Media Façades [10]. This framework allows us to describe *Reveal-it!*! with regards to the key aspects of any urban display system, such as its location and situation, material and form, dataset and data input and visualization design (mapping and animations).

Location and Situation

Considering the situational along with the spatial aspects in the design of public visualization is important, as situations determine the shared understanding and social interpretation of cues in the physical environment [20]. Based on the pre-study and previous work [25] we specifically aimed at creating a situation that supports spontaneous and opportunistic conversations. We thus chose to focus on public and semi-public settings that host informal, opportunistic social activities and encourage informal gathering, dwelling and transition, such as spaces in front of local cafés, inner yards or entrance halls of community centers.

Material and Form

Previous work on visualization in shared settings [37, 43, 45] emphasizes on the seamless aesthetic integration of the display in the physical environment. Therefore, we attempted to mimic the visual style of graffiti, by avoiding the visible rectangular frame of traditional data screens. Our visualization was implemented as a life-size (3x3m) projection, which is suitable to a wide range of physical spaces. This type of low-cost and portable display technology was preferred above alternatives such as LC displays or multi-touch interfaces, as these tend to be too fragile or expensive for a typical public setting.

Dataset

Previous work has used public, comparative feedback to reduce energy consumption by triggering feelings of competition, social comparison or social pressure [45]. Based on our pre-study, which indicated the potential benefits of comparing data averages on several levels, we chose to focus on a dataset that combines private electricity consumption data (i.e. from individual households) with more commonly relevant data, such as the neighborhood and city consumption averages.

Value / Social

Value / Social

Business

Value / Environment Economic

Data Source



Figure 1. The web-form for private data entry loaded in a table interface.

Private Data Entry

We developed a form of personal, yet public, form of data entry that allows any onlooker to voluntarily input their data into the system. We chose to use a mobile interface, to allow multiple participants to simultaneously interact with our system while still keeping some form of privacy. To this end, we created a web-form, which can be loaded on any tablet or smartphone (Fig. 1). This deliberate act of public data entry is also meant to enhance public engagement, as it provides an opportunistic moment at which participants must dedicate their attention to the topic at hand.

The data entry form requested the participant's monthly energy expense (what she remembers to have paid for her last electricity bill), her neighborhood and the number of co-inhabitants in her household. The participant could also provide her name, however this data entry was not made obligatory. Based on observations from our pre-study, we chose to include a monetary value range instead of electrical usage (kWh). Secondly, we made a list of value ranges available, since people generally do not remember the exact quantitative values. Aiming to address the consideration for fairness, the interface required the input of the number of co-inhabitants. Accordingly, the system normalized the reported electricity bill by the number of co-inhabitants to derive an estimated consumption value per participating household member. While there are admittedly many additional (and difficult to capture) factors that contribute to the real average consumption within a multi-person home, we believe that this estimation proves sufficient to evaluate our research goal.

Visual Mapping

The observations from our pre-study support previous results in literature, which suggest that visually distinct interfaces, visual aesthetics and animation have the potential to promote curiosity and initiate participation [22, 44, 46]. We chose a visualization technique that combines the “seriousness” of the topic with the more accessible style of popular infographics. The visualization consists of an abstract sunburst representation [40], of which each burst (Fig. 2.A) corresponds to the energy bill of an individual household participant. The circular visualization technique allows for scalability and hence an arbitrary number of people to be represented. Upon data entry, the participant's name (if provided) appears in two distinct places: in the center of the sunburst graphic as a textual statement “X spends Y €!” and at the end of the corresponding burst, as a

Data Source

Value / Psychological

Data Source / Entry

Key Activity

Value / Psychological Proposition

Data Offering

Figure 91 Open Coding Process of Case Study 6 on Text

Table 66 Key Codes of Case Study 6

Open Codes	Codes from Text	Axial Codes
Data Source	Data sets of energy consumption Crowd-Sourced Data through Mobile Interface (2)	Input - Stored Input – Real Time Application - Interface
Data Offering	Exposing Underlying Patterns Insights about human response Insights about human perception Insights about Human Interaction Representation (2) Dynamic Visualisation	Output / Analytics Output/ Analytics Output / Analytics Output / Analytics / Intervention Modelling Modelling / Interface
Data Handling	Use Design Framework Data Entry Estimation	Input – Stored Input Analytics

	Transformation		Modelling
Value	Social	Increase Social Awareness Increase Understanding Shared Understanding Supports Interaction Encourage Gatherings	Output / Intervention
	Economic	Enhance Energy Consumption (2) Reduce Energy Consumption	Output / Intervention
	Psychological	Public Engagement (2) Promote Curiosity	Intervention
Value Proposition	Public Interactive Projection Social Electronic Communication Playful Data		Application – Interface
Business	Life-size Public Visualisation (3) Urban Communication tools Social Visualisation		Application – Interface / Smart Materials

Case Study 7

2. THE SENSPOSITIVE LOGIC

Value	The Integration of Information Technology (IT) in architecture during the last decade has opened up a path to the creation of Schodek's "empathic" space within which human activities can be understood in the appropriate context by a system [8]. Along this path, sensponsive architecture targets the emergence of a spatial, assistive 'consciousness' that is seamlessly integrated into human daily environments. Sensponsiveness adopts the Ambient Intelligence (AmI) framework of ubiquitous, yet invisible, computing to orchestrate the collaborative function of technological systems that collect human-activity and environmental related data, assess it based on qualitative factors and direct the appropriate spatial and ambient changes within the augmented architectural space.
Key Activity Compute. Orchestrate. Collect. Relate. Assess. Direct. Change	Intelligence (AmI) framework of ubiquitous, yet invisible, computing to orchestrate the collaborative function of technological systems that collect human-activity and environmental related data, assess it based on qualitative factors and direct the appropriate spatial and ambient changes within the augmented architectural space.
Business	The sensponsive logic is defined by three basic characteristics: <i>time</i> , <i>understanding</i> and <i>intention</i> . <i>Time</i> refers to the act of providing a spatial response in a timely fashion, <i>understanding</i> refers to the act of monitoring and perceiving the context within which a response will take place, while

intention refers to the act of assembling a pattern of specific responses, appropriate for the conditions and the respective context. *Time* can also refer to delay, which is the time required for a 'thinking' entity to assess a situation, prior to *understanding*. In order to avoid too much complexity, the act of *understanding* aims to recognize specific human activities and behaviors that are deemed important by the designer. Those three characteristics facilitate the design of spatial behavior. Following are the basic components for the operation and set up of a sensponsive architectural space:

- **Activity Evaluation System (AES).** Initially it is important to identify the type and the intensity of the human activities that take place, in **Data Source** relation to time, inside a specific environment. The designer can then set the environmental qualitative characteristics s/he wishes to make responsive.
- **Dynamic Building Program (DBP).** It is a flexible diagrammatic process, which changes in real-time, as it is linked to the AES. It is developed to re-configure its measurements every time the activities and the environmental conditions change. In its current state of development the DBP application examines the relation between optimum arrangements and existing conditions to produce visualizations that highlight the deviations calculated by the system. The purpose is not data precision but the development of a tool that provides better knowledge of space utilization and highlights ways toward efficient solutions in future design. It also enables the design of reconfigurable settings that can adapt to changing spatial requirements. [9]
- **Responsive System (RS).** This system has two modes of operation. The first one is the *interactive mode* and it is fully controlled by the user. During this mode, spatial changes take place instantly in order to provide the best arrangement that supports the human activities hosted within. Re-configurable, kinetic spatial elements allow people to make the appropriate modifications within the allowances of the design. The second mode is the *sensponsive one*. In this mode, the designer shapes the core of the sensponsive behavior. The main attributes that define the performance of human activity are monitored in the most unobtrusive way possible. After a process of evaluation, the system decides whether a spatial intervention is necessary. Evaluation is a difficult task because it carries a high level of objectivity. However, a combination of participatory design, machine learning and argumentation processes can facilitate a self-regulating process. [10] This is when the 'responding with sense' mode manifests itself through the understanding factor, based on intention. The RS employs flexible spatial configurations, smart materials, projections and speakers in

Key Activity/ Relate

**Key Activity
Operation**

Operation

Key Activity

Data Source

Figure 92 Open Coding Process of Case Study 7 on Text

Table 67 Key Codes of Case Study 7

Open Codes	Codes from text		Axial Codes
Data Source	Human Activity Observation Environmental Data Sources Activity Evaluation System Dynamic Building Program Responsive System Sensponsive System Parameters		Input – Real Time / Intervention Input – Stored Input – Real Time / Intervention Analytics Analytics Input
Data Offering	Space Response Human-Centred Design		Intervention - Automated
Data Handling	Adopt Ambient Intelligence Framework Identify Compute Orchestrate Collect Relate (2) Assess Direct Change Monitor Assembling Pattern	Time Understanding Intention	Input Collection / Aggregation Processing Analytics Collection Processing Recognition Processing Modelling Collection / Aggregation Analytics
Value	Use	Empathic Space Spatial Response in Time	Intervention – Automated
	Social	Discreet Response Influence Health Influence Behaviour Influence Performance	Intervention- Automated Output / Intervention - Human
	Economic	Automatic Space	Intervention - Automated
	Environmental	Environmental Adaptation	Intervention - Human
	Psychological	Influence Emotions	Intervention - human
Value Proposition	Space Reconfiguration Scenario Design Smart Materials (Electroactive and Electrorestrictive Polymers)		Intervention – Automated Output / Intervention – Human Application – Smart Materials
Business	Augmented Architectural Spaces		Application - Kinesis

Case Study 8

2.3 Data Management

Architectural Value / Use

Increasing productivity has always been a high priority on a construction jobsite, since it can result in the reduction of time and costs. A productivity analysis is a common practice that measures how productive a jobsite is, based on tasks or trades. The study produces statistical data (e.g., task a takes four times as long to complete than the industry average) that can be used to implement changes to optimize productivity (e.g., "task a" needs an additional worker to complete). Poor materials management can also result in large and avoidable costs during construction. First, if materials are purchased early, capital may be tied up and interest charges incurred

Data Offering

on the excess inventory of materials. Moreover, materials may deteriorate during storage or be stolen unless special care is taken. Second, delays and extra expenses may be incurred if materials required for particular activities are not available. Accordingly, insuring a timely flow of material is an important component for optimizing productivity. A productivity analysis can show at what points in the construction process delays and time wasted exist (e.g., windows were moved to three different locations before it was installed). Again, analyzing the statistical data can be used to implement changes (e.g., windows are placed in a dedicated section until they are needed).

Data offering

Manual productivity analyses are shown to be error prone and time consuming (Goodrum et al. 2006). Yet Radio Frequency Identification (RFID) is one of a few technologies that is utilized to automate a productivity analysis. RFID technology has been shown to have a multitude of benefits from the implementation within various construction sites including asset tracking, inventory management, and on-site security upgrades (Ergen et al., 2007; Grau et al., 2009). Most importantly, its implementation has been shown to be feasible and cost effective (Costin et al., 2012a).

However, a few problems exist that prevent the full implementation of such system for a construction job site. First, the system produces massive amounts of data that is difficult to handle manually and produces data overloads. Second, the data may contain read anomalies such as false negatives, false positives, and duplicate reads, which can ultimately decrease the integrity of the data for analyses.

Key Activity / Filtering

A method using geometric algorithms for air protocol filtering was used to reduce the amount of filtering required before the data is stored in the database (Parks et al., 2009). The method was shown to reduce the amount of meaningless data which ultimately reduces time and cost associated with filtering and analyzing the data. In attempts to solve the problem of missed reads of passive RFID tags, Darcy et al. (2009) proposed a methodology that fuses the use of data analysis techniques and Non-Monotonic Reasoning in order to restore the missing data. Their reasoning engine had an average success rate of 87.7% which is shown to be beneficial. Non-Monotonic Reasoning is further incorporated with Clausal Defeasible Logic (CDL) in an enhanced a cleaning tool that detects any suspicious data sets and eliminates duplicate readings and intrusions (Darcy et al., 2010). The previous algorithms that help eliminate read anomalies have yet to be tested with data produced on construction jobsites.

Key Activity

A proper materials management is an important aspect in the improvement of the productivity and efficiency of a construction project. The automation of the identification and tracking materials with technologies, such as GPS and RFID, has been shown to improve productivity and efficiency. However, a standardized implementation model has not yet been established. Therefore, Nasri et al. (2010) presents a model for the automated tracking and locations of construction materials. The model consists of 1) identifying the needs, 2) project definition, 3) implementation evaluations criteria, 4) implementation options, 5) evaluation of options, 6) deployment process, and 7) measurement and evaluation for next project implementation. The model that is presented is well established for the implementation of the automation of tracking materials. However, the model lacks an in depth evaluation of the results from the technologies and there is implementation of the results. Chen (2009) proposed the Automatic Productivity Evaluation (APE) method that utilizes RFID and GPS technologies to automatically evaluate productivity.

Data Handling

The focus is mainly on worker productivity, i.e., output per man hour, and therefore materials management is not adequately covered, although the methodology can be applied to materials management. Shahandashti et al. (2010) developed a simulation based framework to support the identification of the information requirements for assessing productivity performance of earthmoving, in which RFID was used to assess labour hours and cycle durations. Ilic et al. (2009) utilized a rule-based RFID data analysis to detect inefficiencies, such as shipment delays, theft, or inventory problems in supply-chain management. The generic consistency rules can be applied in a real-time analytics system in order to process streams of RFID. Otondo et al. (2009) investigated the ways managers evaluate and adopt the implementation of RFID technology. The results show that the manager's report a wide range of problems that can inhibit the full potential of RFID technology. Baars et al. (2009) utilized the Online Analytical Processing (OLAP) tool multidimensional data sets for analytical applications as known from the realm of "Business Intelligence" (BI).

3. EXPERIMENTAL ENGINEERING DESIGN

Key Activity

The purpose of this research is to utilize RFID-BIM integration to generate real-time data to produce leading indicators for safety and building protocol control. Additionally, the executed approach is to optimize cost and

Value / Use Economic

Value / Use schedule while maintaining the scope, quality and performance. One of the many goals of the innovative project delivery models implemented on this site is to enhance quality control by reducing rework or damage of finished work.

Value / Use The UCSF Medical Center team partnered with a commercial RFID technology provider in order to implement RFID-based tracking devices on the project. These devices are a proposed solution to the sequencing, safety and quality challenges previously mentioned. The RFID based building access will ensure more visibility and tracking of the equipment, materials, and personnel entering and exiting the jobsite while also allowing for the project team to increase work planning efficiency. RFID technology will present measures and data to help prevent these issues. The data analysis will allow for more efficient planning and work flow. This method of planning will help limit the amount of rework performed and limit access to zones where work has been completed, helping to limit damage. The entry security as well as asset and personnel tracking will help enhance the safety of the job site. Figure 1 displays the control center for data gathering, analysis, and communication of the system. The data can be transferred and stored on a central cloud server.

Key Activities
Gathering, Analysis, Communication.

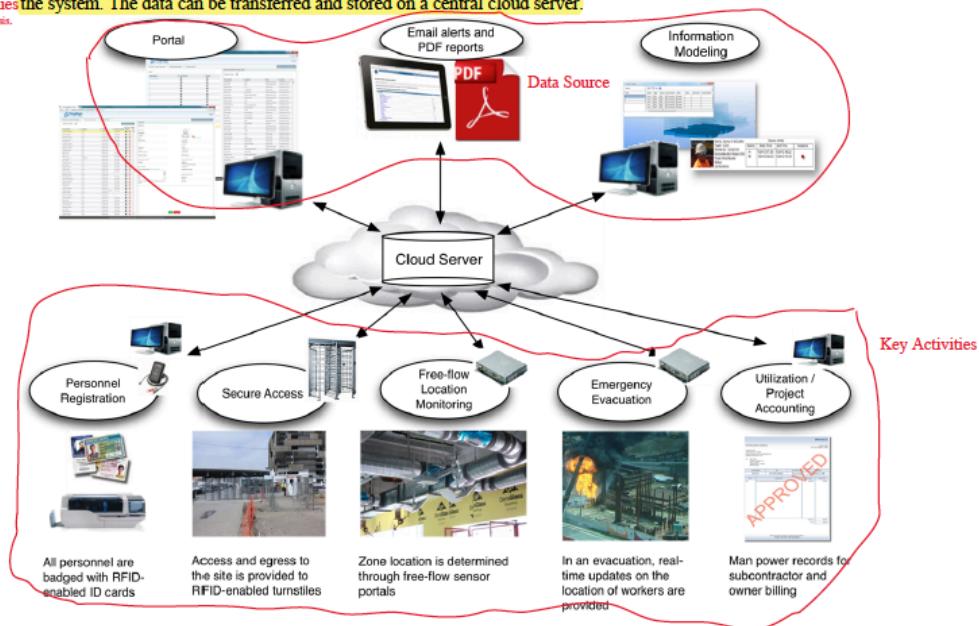


FIG. 1: Control center for data gathering, analysis, and communication.

Activity / Identification Each person who enters the site (e.g., workers, subcontractors, visitors) would register and receive a UHF-RFID-enabled identification badge with breakaway lanyard (Figure 2). They would each be defined as an *IfcActor*. All construction personnel are required to wear the badge plainly visible. When entering the site, the person must manually tap the badge in front of the RFID reader of the turnstile for single entrance. This process ensures that only a single authorized person can enter the site at a time. Multiple turnstiles are used to avoid congestion and delay of entry and egress. Approximately 80 RFID tag readers were installed in the infrastructure of the new building and multiple secure turnstiles with tag readers were places at the access points for each work zone (Figures 3 and 4). Since the readers are fixed, they can be classified under *IfcBuildingElement*. The associated property sets of *IfcBuildingElement* include manufacturer, warranty, and environmental impact indicators, which can all be used for RFID readers.

4. DATA MANAGEMENT

4.1 Data Collections

Data Activity The system generates real-time data which is then filtered and stored for later use. The real-time data reports the current location of a tag being read, along with any additional data the user chooses (such as tag ID, name of the worker, and trade). The system can support real time notifications in addition sending the reports via email. All the real-time data is then stored to a cloud-based web portal where real-time email notifications and reports can be delivered daily. The stored data can then be used for analyses or reports. In addition to this reporting, a web service has been created in order to provide external software clients access to the data. This is done so the data

Figure 95 Open Coding Process of Case Study 8 on Text

Table 68 Key Codes of Case Study 8

Open Codes	Codes from text		Axial Codes
Data Source	Building Information Modeling Cloud Server Location		Input – Stored Input – Real Time Input - Location
Data Offering	Real-time tracking Statistical Data Asset Tracking Inventory Management Zone Occupancy Activity Analysis Number of Works Visualisations		Collection – Real-time Input – Stored Intervention – Automated Intervention – Human Output Analytics Output Application - Interface
Data Handling	Integration (2) Simulation Modeling (2) Algorithm Filtering (2) Analysis (2) Aggregation (Data Reduction) Reasoning Evaluation Utilisation (2) Gathering Communication Identification Generation	Identify the needs Project definition Evaluation criteria Implementations Options Deployment process Measurement and Evaluation	Analytics Modelling / Future Modelling Analytics Aggregation Aggregation Aggregation Processing Processing - Analytics Gathering Modelling Processing Analytics
Value	Use Social Economic Environmental	Easier Evacuation Safety and Security Control (2) Regulations (2) Efficient Planning Effective Workforce Increase and Optimise Productivity (3) Time Cost (3) Schedule Limit Damage Resources Tracking and Protection Optimise Material Use Quality (2) Impact	Output / Intervention – Human Intervention – Human Output / Intervention - Human Output / Intervention - Human Output / Intervention - CAE
Value Proposition	Event-Based Response Real-time Automated Job Site Real-Time Digital link between virtual model and Physical Components		Intervention - Real Time Intervention – Real Time – Human Intervention - Automated
Business	Real-time Notifications Real-time operations Performance Metrics		Application – Interface Intervention - human

Appendix 2: Terminologies

Hitchhiking	<p>An approach in Information Technology for anonymous collection of sensed data in location-based application. This approach considers the location an entity of interest rather than the people who are using it. This guarantees the privacy of the people while providing sufficient information about the location.</p> <p>According to Tang et al. (2005) "Hitchhiking has seven requirements:</p> <ol style="list-style-type: none"> 1) Location is computed on the client. 2) Only the client device is trusted. 3) Each person approves reporting from a location. 4) Physical constraints prevent location spoofing. 5) Location identifiers are based on physical location. 6) Location identifiers are generated by the client. 7) Sensed identifiers are not reported to the server"
Census Block	A unit that is used in statistics to indicate a specific area. This unit is defined by visible and nonvisible boundaries. Visible boundaries are represented with features such as streets, roads, streams, and railways. The invisible boundaries are represented by nonvisible limits such as property lines, cities, school districts. The Census Bureau tabulates 100-percent data. (Factfinder.census.gov, 2014)
Industry Foundation Classes	A BIM developed product data model for the AEC industry that is used to exchange information of the design and the full life cycle of buildings. The IFC is supported by the IAI (Eastman et al., 2011).
Theoretical Replication	Multiple-case studies chosen for the case study analysis to cover different theoretical conditions of the same theory (Bengtsson, 1999).
Operational Model	Operating model is an abstract or visual representation of how an organisation delivers value and how the organisation runs itself. It reveals the integration level of the business process and the standardisation of delivering goods and services to potential customers (Ross, Weill and Robertson, 2006).
Telematics	The use of telecommunications, sensors instrumentation and wireless communications to exchange information
Stochastic Model	It is a tool for determining distributions of potential outcomes by predicting random variation in one or more inputs over a period of time (Brzezniak and Zastawniak, 2000).
Ultra-wideband	A short-range radio technology that uses low energy. An example of this is Beacons and Computer Peripherals.
Voxel	Voxels are equal to pixels but exist in 3D spaces. Voxels represent values on a regular three-dimensional grid (Chen, 2000).

Voxelisation	The conversion of 3D geometric objects from their continuous geometric representation into a set of voxels that best approximates the continuous object.
Watertight	A 3D model that does not have any holes or borders and prepared for 3D Printing, usually exported in STL file format.
XML	<p>XML is a computer language used to create user-defined mark-ups of documents and encoding systems (Goldfarb and Prescod, 2001). XML language design is simple and allows human readability (Nurseitov et al., 2009). An example of XML file for some books:</p> <pre> <Books> <Book ISBN="0553212419"> <title>Sherlock Holmes: Complete Novels... <author>Sir Arthur Conan Doyle</author> </Book> <Book ISBN="0743273567"> <title>The Great Gatsby</title> <author>F. Scott Fitzgerald</author> </Book> <Book ISBN="0684826976"> <title>Undaunted Courage</title> <author>Stephen E. Ambrose</author> </Book> <Book ISBN="0743203178"> <title>Nothing Like It In the World</title> <author>Stephen E. Ambrose</author> </Book> </Books></pre>

Appendix 3: The Case Studies Analysis Matrix

The Analysis Matrix is a flat representation and mapping of the data operational components of the case studies. The eight columns represent the case studies, while the rows represent the different data operational components. The X symbols mark the existence of that specific component in the associated case.

The Matrix allows an understanding of the relationship between different data operational components and reveals how they contribute to achieving the allocated Value. The Analysis Matrix was generated during the coding and the analysis stage of the various cases. The matrix aids the constructing of the various categories.

Appendix 3: The Case Studies Analysis Matrix

Figure 94 The Case Studies Analysis Matrix

Appendix 4: Conference Paper

The following figures show snapshots of an accepted conference paper that will be presented at the eCAADe 2017 conference in September in Rome, Italy.

A value-driven perspective to understand Data-driven futures in Architecture

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This paper reports on an investigation of the potentials of data utilisation in Architecture from a value generation and business creation points of view, based on an ongoing PhD research by the first author. It is of crucial importance to, first, identify what data actually signifies for Architecture, and secondly to explore how the value obtained through data-driven approaches in other industries could potentially be transferred and applied in our professional context. These objectives have been achieved through a qualitative comparative analysis of various cases. Additionally, the paper discusses the multiplicity of factors which contribute to different interpretations and utilisation of data with reference to various value systems embedded into our profession (e.g. design as ideology, design as profession, design as service). A comparative analysis of the existing data utilisation methods in connection with various value systems provide crucial insights in order to answer the following questions: How can data assess values in architectural design/practice? How can data utilisation give way to the emergence of new values for the profession?

Keywords: Big Data in Architecture, Data-Driven Architecture Design, Data in Architecture Design, Computational Data Design, Digital Value in Architecture

Introduction

Big Data is a common trend, a buzz word and a broad term concerning large amounts of data that is generated, collected and analysed to provide valuable insights and improve businesses. Many industries have experimented and harnessed the benefits of using Big Data in their businesses, and hence, new business channels and disruptive techniques have emerged which provide the necessary intelligence to elicit, process and make sense of data (Manyika et al., 2013). An analytical report (Manyika et al., 2011) indi-

cated construction sector as the least beneficiary and falling behind other sectors in the utilisation of data in decision making and knowledge discovery. However, using data in the AEC industry is not new. Data is fundamental to the architectural design and production where both architects and engineers continuously create, modify, share and simulate data. In this respect, data already underlies much of the modern AECO (Architecture, Engineering, Construction and Operations). However, what is new to the industry is the amount of data that is currently avail-

able to us and our improved capacity to share, capture, measure, compile, process and translate data into meaningful and actionable information through smart technologies, enhanced data standards and visualisation techniques (Barista, 2014).

Existing research identifies two immediate problems that impede the adoption of data tools within architectural design firms; first is the lack of efficient means to translate and systematize very large and unknown data sets for efficient use; and second is the lack of knowledgeable data experts within design firms who can intelligibly curate diverse data sources and tools according to the project needs (Deutsch 2015). The proposed paper contributes to the existing research by bringing in the "value" perspectives in order to understand how the different value systems embedded in "architectural design" and "architectural practice" will affect the ways in which data is used and adopted in our profession. The "value" perspective is being raised for two main concerns surrounding architectural profession. The first is the lack of a common understanding of the role architects entail in terms of their contribution to the society. An online survey published in 2012 by the Architect's Journal showed that participants were not aware architect's responsibilities (Thompson, 2012). These results were confirmed by a survey (Samuel, 2015) questioning the value that architects bring inside and outside the profession. There is clear evidence to suggest that this value is not clear neither from the point of view of architects, nor clients or other stakeholders in the sector (Petrie, 2016). The second concern is the extensive concentration on the economic (cost) value of architecture. A recent report by RIBA points out how "austerity and the focus on cost have diminished trust in the value of architects' work" in UK (RIBA, 2015). Reed, the former president of RIBA, indicated to another potential danger of diminishing the quality of life that good design brings and emphasises the necessity to identify the value created by "thoughtful and responsive architecture". (RIBA, 2011). A recently published report by Arup in collaboration with RIBA addresses the

radical transformation in the design of buildings and cities through data-driven approaches and methods (RIBA, 2013). One of the repercussions of these new approaches is the transformation of our perception as to what counts as a "sustainable" design solution. Sustainable design solutions are now expected not only to be "green", but also intelligent and interconnected and thereby introducing new "economic" and "social" value (Kocaturk, 2017).

Architects rely on and are affected by different types of data in their design and decision-making process. Incorporating data into the design process is not a new concept as architects have been doing that since the beginning of the profession (Deutsch, 2015, p.1). What is new today is the vast amount of digital data that is easily available for low cost and effort (Gupta, 2016). This phenomenon has been described by two fashionable concepts: Big Data and the Internet of Things (IoT). Big Data and the IoT have already influenced new operations and business models to emerge (Manyika et al., 2011) outside Architecture. In order to understand their potential impact on Architecture, it's crucial, as a first stage, to understand what "data" signifies in architecture and for our sector. To this end, this paper identifies "data", primarily, as a driver for the emergence of new values in Architecture and an added-value technology to the built environment and AEC industry at large. The paper specifically aims to contribute to the current Big Data discussion in our industry by synthesising the technological and business potential of Big Data and the IoT (Internet of Things) in order to identify their potential to expand the definition of what we deem as "value" in Architecture.

This paper provides insights into the different components of data-driven models in Architecture with recommendations for possible future implementations. In the following sections, the paper first explores the dynamic and intricate relationship between data and architecture, and reveals patterns of data utilisation in response to varying perceptions and reproductions of design in varying contexts, namely: design as ideology, design as profes-

sion, design as service. This provides a deeper understanding of the relationship between how the data is obtained, the purpose its use, and the value it generates for the processes and products of design. This is followed by a more contextualised discussion on Big Data and the Internet of Things (IoT) and the potential they entail to facilitate the emergence of new operational models in our sector. Finally, the paper reports on the analysis of 8 cases set-up to identify various data-implementation approaches in design across different sectors. This leads to the development of a framework for data implementation and operational model that can be adopted in the architectural profession.

Data in Architecture Design

Data in architecture design has long been associated with the standard resources of technical data such as the likes of Neufert, Time-saver Standards and the Architects' Handbook. These books provide a comprehensive range of technical information for architects regarding the standards and requirements of the different types and aspects of buildings. These data do not have any impact on the design unless the architect consciously searches and applies the selected solution to the design. Data has therefore been seen as simply inputs which architects are required to connect and transform into meaningful designs. Data is mostly understood as constraints and opportunities and rely on architects' reasoning capabilities and institution to influence design decisions.

Data and information utilisation in and for architecture reveals specific patterns according to the varying perceptions and reproductions of design: design as ideology, design as profession and design as service. Architectural design as ideology focuses on the design of forms which respond to perceived social needs with underlying theoretical assumptions. It goes beyond the pragmatic function of architecture and largely associated with the cultural and ideological positions taken (by the architect). The data which drives the ideology is often qualitative, symbolic, philosophical and unquantifiable. The

design process depends on the architect's intuition, his personal ideological and subjective standpoint. Most architectural styles are ideological in their core. Design as ideology provides a system of values based on symbolic meaning.

Thinking of architecture as a profession rather than an ideology eludes its deep connection with its social, political and cultural roots, and rather focuses on the economical and market values. Architecture as a profession focuses more on the functional and economic value generated from its pragmatic function. This representation of architecture is relatively contemporary and came into play with the increasing influence of capitalism (Mako, Lazar, & Blagojević, 2014). Also, architecture as profession is mostly driven by the market, which it dictates its principle values and trends (De Graaf, 2015).

Architecture as a service focuses on the design process rather than the artefact. This perspective extends the design process to consider the overall service-life of the product (the building) including after-sales (post-occupancy). Architecture as a service sits somewhere between the previous two (as profession and as ideology). Data that drives architectural design as service usually aims to enhance the overall building performance and quality. In other words, data is aimed at improving value within the performance.

The redefining of data in the above table shows that data serves more than just an "input". Its role extends and allows other values to emerge. It becomes quite clear that value is the main objective when assessing data and that the achieved value is crucial in understanding how data could be employed.

Design as	Data source	The role of data in process	Assessment
Ideology	Intuition, Inherited	Guidance	Symbolic
Profession	Market	Meeting markets need	Market
Service	Process	Evidence	Performance

Value form Data

Data goes through different procedures to allow "new value" to emerge. In the past, the role of processing such data has been the responsibility of the

Table 1
Data in Design as
Ideology, Profession
and Service

architect solely. However, with the rise of digital technologies and the increase of data volume, this role has changed slightly, allowing the machine to interpret data and to provide new insights. This change affects the role of architects and extends his/her capabilities.

In this context: The Data, Information, Knowledge and Wisdom [DIKW] pyramid provides a preliminary understanding of how various processes affect data. Our own interpretation of the DIKW pyramid is created (Figure 1). The pyramid shows that value is an output of all data processes. Value can be obtained at any stage. The more effort leads to more specified and deeper value.

Architect skillset and intuition are keys for the interpretation of data. A survey carried on by Samuel (2015) showed the different types of architects and their skillsets in the profession. The survey listed four types of architects: Social, Commercial, Cultural and Technological. Comparing these types of architects shows differences in data utilization, the achieved value and the communication of this value.

Data does not disappear when the value is achieved but somehow transform into design decisions, objects and facilities. With the advancement of technology, it is possible to keep track of data and allow it to be reinterpreted in the design process iteratively. An example of this is the reuse of stored data from metadata and sensors which are embedded in spaces to refine the design. The space itself is a product of a design decision that is based on data, and at the same time it has sensors that collect data. Data processes are not linear as the output can be reused as an input again.

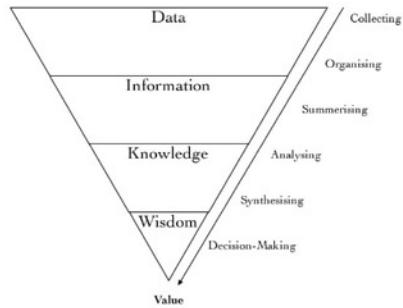


Figure 1
Value and DIKW
Pyramid

Architect's Role between data and intuition

When employing data, in addition to reasoning, architects rely on their intuition and that creates their creative impulse (Linsey, 1998). This intuition is intangible and not observed but can be partially described. Intuition determines the difference in the evolution of the design artefact and processes employed by between different architects even when they use exactly the same data.

According to Deutsch (2016) The decision-making spectrum in architecture is either Subjective or Objective based on the input type. Taking design decision based on quantifiable data is considered an objective approach while taking design decision based on unquantifiable data is subjective. The subjective approach is based on intuition and emotions. Figure 2 displays the continuum of decision-making.

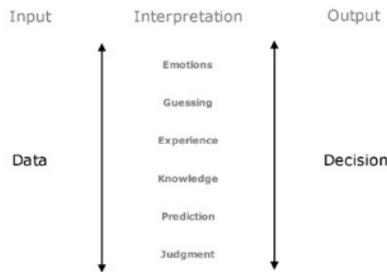


Figure 2
Decision making
spectrum (Deutsch,
2016)

However, this analogy and understanding is not totally accurate. The reason is that data and emotions are presented on the same level as separate interpretations in the spectrum while they are not. Data are not the opposite of emotions. On the contrary, data may as well allow the emergence of new emotions. In fact, data becomes a facilitator of all interpre-

tations in the decision-making spectrum. An example of emotion-based data interpretation in design is Singh's (2013) Emotion-Centred Framework for design innovation. In the diagram below, a refined diagram (Figure 3) of the decision-making spectrum in architecture is suggested. In this diagram data informs different interpretations and eventually allows decisions to take place.

Figure 3
The refined decision making spectrum



Big Data, the Internet of things and Data-Driven models in Architecture.

Different technologies affect the type of different operational models adopted in Architecture (Grobbman, 2008; Picon, 2010; Riccobono, & Pelitteri, 2014). These technologies proposed different operations and altered the workflows. An example of these disruptive technologies is the introduction of Computer Aided Design [CAD]. Although CAD was never meant to be disruptive and its underlying motivation in early sixties was to replace the manual drafting process as a cost-effective and efficient alternative, it opened new paths for other technologies to emerge, e.g. increasing use of 3D data, the possibility to share data/information, and new paths for collaboration; which eventually led to the development of Building Information Modelling [BIM] (Isikdag, 2015).

Architecture and construction are complex processes that rely on the use of data. They operate using two-dimensional and three-dimensional data. Architecture handles financial and corporate records,

documents, and schedules. In addition to that, the post-completion of the construction process keeps generating an enormous amount of data on a daily basis. The buildings are becoming hubs of sensors, metres and wires. Data is increasingly digitised. What was impossible in handling data before, became probable today with current Big Data technologies. Big Data and the Internet of Things in Architecture can be defined as significant amount of data generated or acquired through the design, the construction and the occupancy of the built environment, including data generated by designers, constructors, the building, and post-occupant users.

There are certain challenges that contribute to adopting Data-Driven approaches in architecture. One of the challenges is the extra time and effort involved in the process (Sailer, Pomeroy, & Haslem, 2015; Deutsch, 2015). The move to Data-Driven techniques is considered a leap in design operations that requires extra training, resources and time, of which the accurate gain is unverified. This situation creates a risk that most architects prefer to avoid. The change in the processes will undoubtedly affect the current culture of architectural profession and education (Deutsch, 2015). Another challenge is the number of disciplines (and stakeholders) involved in the sector where Architecture operates and the need to efficiently address, manage and integrate data across those disciplines (Mahdavi, Martens, & Scherer, 2014, p. 585). Also, Data is seen too abstract and somehow restricting the design process (Deutsch, 2015). The last challenge is due to contractual complexity (Miller, 2012) and the uncertainty around who owns the data and the liability for the project outcome.

RIBA (2013) has identified four general approaches to working with data for architects, urban designers and planners. These approaches are: (i) meeting users' needs, (ii) experimentation and modelling, (iii) analysing data to improve local and national policy making and implementation, and finally, (iv) improving transparency to speed up development processes. These approaches to data handling are proposed as a refinement to what architects

already do rather than a change or reformulation of the way architects operate. Also in this report, there is no indication and clarification for the actual operations of these data approaches and the achieved values. We argue that Data-Driven operations have the potential to expand the current use of data and introduce new models of operations in architectural profession. These new models introduce new perspectives and methods of embedding data into the design process.

Case studies Analysis, Methods and Grounded Theory

The previous sections identified the correlation between data and value. We explained what data mean to architecture and how Big Data affects the architecture industry. We also identified the need to uncover data operations and indicate how value is created. In order to achieve this, various cases have been collected and analysed inductively following the principles and methods of Grounded Theory. This section will describe the selection and analysis of eight case studies in order to reveal the hidden data processes that are employed in the design.

The cases are analysed following two methods: The first is concerned with the process and operation of utilising data to allow values to emerge. This was achieved following the grounded theory methodology. The second is focusing on the value and how the digital data address value. This was achieved following a digital value assessment. The case studies are conducted to achieve the following objectives: Identify the main components of the architecture data-driven operation in design; Identify the data-driven operational models in Architecture Design and the relationship between the architecture data-driven operation components; Identify the types of values that emerged; Propose a structured understanding of the data-driven operational framework.

The first and main method is the Grounded Theory, which is a systematic methodology that permits the construction of theory through the analysis of data (Glaser & Strauss, 1967). It is employed for

its capability of explaining complex phenomena, of which there is some ambiguity, and its ecological validity that represents real-life settings. The Grounded Theory is based on continuous coding procedures: Open, Axial, Selective and Theoretical. These coding procedures allow the emergent of themes, categories, concepts and theory through the analysis process. The data must reach a level of saturation in order to consider the theory valid (Charmaz, 2014). The Grounded Theory has its own validation criteria and should be judged according to them. These criteria are: fit, relevance, workability, and modifiability (Glaser & Strauss, 1967).

The second method is the digital value assessment. This method aims to understand how the digital operation in these case studies enables other types of value to emerge, we present a concept of the Digital Value Equalizer. The equaliser is merely a conceptualisation and representation tool used to show tangible values that are enabled through the digital value. The Digital Value Equalizer offers flexibility as values are added according to the case and can be adjusted according to its impact. Some of the architectural values depend and affect other values and this will affect how the Digital Value is enabling them. This conceptualisation of digital value is adopted in analysing the case studies and coding the obtained value in each case. Figure 4 shows the equaliser in a neutral representation.

Figure 4
Neutral representation of the Digital Value Equaliser

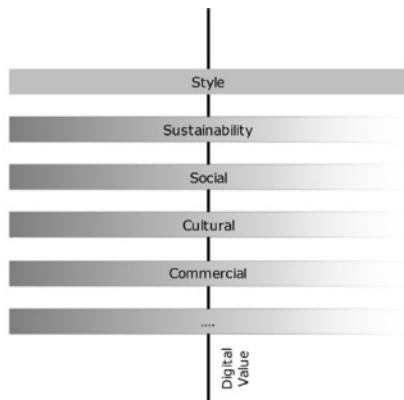


Figure 5
Case Study 1 Digital Value Equaliser

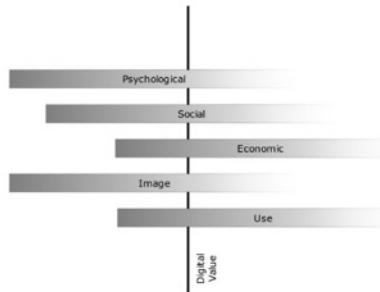


Table 2
Selected Case Studies

It is important to mention that regarding the definition and the vast domain of Big Data and the Internet of Things, it is almost impossible to find one single case that covers all aspects of the technology. There-

fore, it was necessary to consider several cases where data was utilised in a definite scope, in different contexts. The limited scope made each case manageable and consequently, the analysis provided more concrete results. Eight cases had been analysed; each with specific and distinct objectives, collectively covering a wide range of data operations applied in current practice. The cases are cross-sectoral. The case studies selection was a continuous process that concentrated on constant collection and comparison of data/information obtained through these cases until reaching a theoretical saturation of data.

Initial criteria for selecting the cases were established following the rational mentioned above and fulfilling the following:

- The case is chosen from the academic or the practice field
- The case has data implementation through design context with no regard to the phase or level of implementation
- The case provides a solution where one or more architectural or urban elements are involved
- The case has one or more technological methods of data integration, analysis and application

Table 2 shows the selected cases and the industry in which it exists. Table 3 provides a brief description of each case and the theme of data it resembles.

#	Case Study Title	Domain
1	Liverpool Pedestrian Visualisation Project	ICT
2	Chicago Energy Map	Governmental Data
3	Campus Information and Knowledge Modelling	Management
4	Four Chairs and All Others	Product Design
5	Human Behaviour and spatial configuration	Office Design
6	Reveal It, My Position	Urban Screen
7	SIG 04	Architecture / Machine
8	Hospital Project Using RFID	BIM / Construction

#	Case Study Title	Description	Data Theme
1	Liverpool Pedestrian Visualisation Project	A project based in Liverpool, United Kingdom, where data are collected through sensors implemented within Liverpool 1 shopping area to measure pedestrian footfall.	Pedestrian Data
2	Chicago Energy Map	An open data project of the city of Chicago, United States. This project provides energy information through online portal for occupants through various visualisation.	Open Data
3	Campus Information and Knowledge Modeling	An academic project based in the Georgia Tech Campus. The project aims to build a knowledge base of the campus environment which both Building Information modelling (BIM) and Geographic Information Systems (GIS) to assess campus planning and management.	Micro Urban Data
4	Power Chairs and All Others	A generative non-linear design project that utilises data and existing 3D models to generate a new design. The project explores the concept of proximity fusion. The data addresses cultural and social aspects.	Data to Product
5	Human Behaviour and spatial configuration	An academic project that utilises different methods to collect data about human behaviour to inform the design of spatial configurations.	Evidence Based Data
6	Reveal It, My Position	A project that utilises occupants provided data to project information through public spaces.	Social Visualisation
7	SHG-04	A project that establishes architecture as a machine. It employs an architectural system for People, Places, and Things which analyses occupant's behaviours and needs, based on specific data exchange.	Responsive Architecture
8	Household Project Using RFID	A project which combine the use of Building Information Modelling (BIM) and real time tracking sensors to manage construction site.	Operational Data

Components of the Architecture Data-Driven Operation

For assessing the data operations in the case studies through the Grounded Theory, initial themes were used in the Open coding. These themes were identified through a thorough analysis of literature on data-driven businesses outside our industry. These themes have been identified as: Data Sources, Key Activity, Offering, Target Customer, Revenue Model, Specific Cost Advantage (Hartmann, Zaki, Feldmann, & Neely, 2014). Through continuous Open coding of the cases studies, these themes have been gradually refined to suit the studied context and the following themes have emerged: Data Sources, Data Handling, Data Offering, Architectural Value Proposition, Value Channels. Table 4 explains these categories in more details.

Data Sources	The source is identified by the type and hierarchy of stored and streamed data.
Data Handling	The computational process of acquiring, processing and applying data
Data Offering	The output of the Data Handling process in the specific context of the case
Architectural Value Proposition	The values realised in each case. These values are applicable in an architectural context, have the potential to contribute to the emergence of new value systems in architecture, and possibly have an impact on the AEC practice.
Architectural Business Channels	The business strategy which the AEC can adopt. This strategy includes the channels for promoting values in the built environment.

Data-Driven Operational Models in Architecture

An Axial coding of the case studies was completed to connect the Open coding themes which emerged in the first procedure of the Grounded Theory analysis together by identifying relationships through data operations. The Axial coding had two procedures: Horizontal and Vertical. The Horizontal Axial coding revealed the operation of each case in isolation. The data operation consisted of several components, some components allowed human intervention (e.g. by the architect perspective, or occupant). Each case had been represented in a separate diagram of how these components are inter-connected. Figure 6 shows the Horizontal Axial coding of case study 1 as an example.

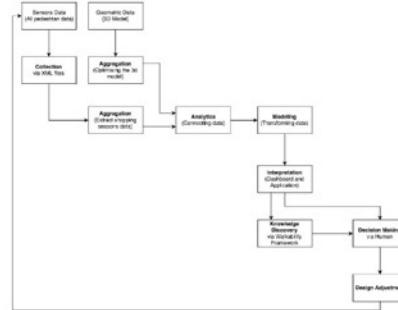


Table 3
Case Studies Description

Figure 6
Horizontal Axial Coding of Case Study 1

Table 4
The basic themes of the Open coding

Figure 8
The Data-Driven Operational Framework in Architecture

is the Collection and Gathering process (Figure 7), it simply allows direct decision making by human. It also provides an output in the form of information, and finally it serves as an input for the subsequent process of Aggregation and Processing. Table 5 provides an initial definition of each process.

Figure 7
The Vertical Axial Coding of the Case Studies

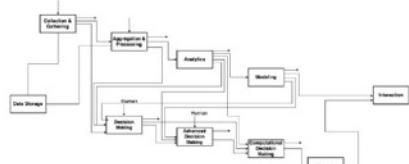
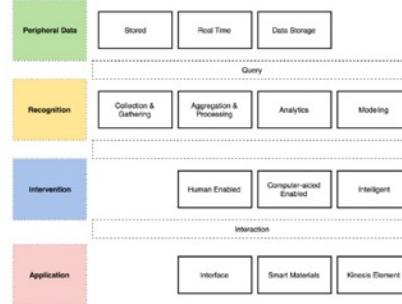


Table 5
Operational Processes of Data-Driven Models

Process	Definition
Collection and Gathering	The simple process of collecting and gathering data of all types with no operations on data.
Aggregation and Processing	The process of selecting and deselecting certain types of data for initially identified purposes.
Analytics	The process of coding, applying algorithms, and connecting certain types of data following set of rules.
Modeling	The process of transforming data from one format into another, such as visualising text and numeric data.

Data-Driven Architectural Operational Framework

The last procedure in the Grounded Theory Analysis is the Theoretical coding. The Theoretical coding revealed the phenomenon represented in a Framework of Data-Driven Operational Models. The Theoretical coding of the case studies proposed four main levels of data implementation, namely: Peripheral Data, Recognition, Intervention and Application. Each level has its component, and each of these components has its properties. Various types of Data were pointed out: Stored, Real-Time and Future, some of these are open data. The recognition of data was identified through these operations: Collection and Gathering, Aggregation and Processing, Analytics, and Modelling. Human Intervention and interaction happens on three levels: Human-Enabled, Computer-aided Enabled, and fully Automated. Finally, the application of data-driven is outputted through: Interface, Smart Materials and Kinetic Architectural Elements. Figure 8 shows the Data-Driven Architectural Operational Framework.



Conclusion

What data means and signifies for architecture and the built environment is a question that needs to be reconsidered. The paper argued that data is more than the representation of the smallest unit in the complexity of a design process. It is a transmittable component of design knowledge and a value generating input for all operations. Instead of proposing a new definition of data in/for architecture - the paper aimed at bringing a value-driven perspective and understanding of data. Following this perspective, and through the analysis of 8 cases across different sectors, the paper developed a new data-driven operational framework for architectural profession.

The use of Grounded Theory aided the construction of new themes and concepts for the development of the proposed operational framework. The Digital Value Equaliser - which was specifically developed and used for the case study analysis - revealed numerous (hidden) values that were critical to the understanding of the phenomenon and had been instrumental in building the framework.

While the research is still in progress, the presented results provide a deeper understanding of how knowledge discovery and decision making in the AEC is affected by adopting a data-driven approach. Future work will focus on the levels of automation in data-driven design processes in response to the varying levels of human and machine interven-

tions driven by computational processes.

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