Development of a Computer Mediated Multidisciplinary Design Protocol and its Application to the Early Architectural Design Stages

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CERTIFICATE OF ORIGINALITY

This is to certify that I am solely responsible for the work, which has been submitted within this thesis. Apart from where identified, by means of referencing, I confirm that the contents of the thesis are original and my own. I confirm also, that no part of the thesis has been submitted to any other institution or body in consideration for any other degree or qualification.

Marianthi Leon …………………………………… (Signed)

……………………………………………………… (Date)

"Fairy tales typically do not apply in real life"

Imre Horváth, Regine W. Vroom (2015)

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ACRONYMS AND GLOSSARY

Acronyms

AEC	Architecture Engineering and Construction
AR	Augmented Reality
A.T.	Architectural Technologist
BIM	Building Information Modelling
BS	British Standards
B.S.	Building Surveyor
CAD	Computer Aided Design
CAVE	Cave Automatic Virtual Environment
CDM	Construction Design Management
CDSP	Conceptual Design Stages Protocol
COBie	Construction Operations Building Information Exchange
CSCW	Computer Supported Cooperative Work
CSCD	Computer Supported Collaborative Design
D.M.	Design Manager
D-B	Design and Build
DBB	Design Bid Build
DQI	Design Quality Indicator
FG	Focus Group
FM	Facilities Management
GUI	Graphic User Interface
HCI	Human Computer Interaction
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
IPD	Integrated Product Development
M&E	Mechanical and Electrical
PPP	Public-Private Partnership
P.M.	Project Manager
PFI	Private Finance Initiative
Q.S.	Quantity Surveyor
RIBA	Royal Institute of British Architects
TUI	Tangible User Interface
UbiComp	Ubiquitous Computing
VR	Virtual Reality

VW	Virtual Worlds
2D	Two Dimensional representation
3D	Three Dimensional representation
4D	Four Dimensional representation, including time

Glossary

Design Process	A series of steps for building a description of an artefact, building process or instrument to meet certain criteria and limitations (Tong, Sriram 1992).
Moderator or Researcher	The writer and researcher of the thesis.
M.S. PixelSense	Microsoft Surface PixelSense is a Tangible User Interface that allows interactions and recognises input when touching the screen, through vision-based interaction. The display identifies what is touching the screen and translates the information accordingly (Samsung SUR40 with Microsoft® PixelSense™).
Physical and analogue design mediums	The traditional/conventional design tools, like drafting instruments, pan and paper, tracing paper, coloured markers.
Parts and Stages of a Study	During the Thesis, a number of studies are described. Each of them is divided in three parts, with the second part each time having an additional division in two stages.
Design Protocol	A design process with clearly defined steps.
Protocol Analysis	A method for analysing complex behavioural processes, like problem solving.

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This work is dedicated to my family! :)

ABSTRACT

Effective multidisciplinary design collaboration and increased effort during the feasibility and early design stages in architecture provide the greatest potential for added value and overall success of a built environment project, from the initial design to construction and operation of a building. This can be facilitated, supported and promoted through human-computer interactions' technologies that allow the integration of physical and digital realms.

The aim of the thesis is to investigate the concept design processes assisted by computer mediation for bridging smoothly the pre Building Information Modelling stages and the concept development with the more advanced design stages in an efficient and effective way. For that purpose, an extensive literature review and a number of interviews with senior practitioners of the Architecture, Construction and Engineering industry assisted in clearly identifying the design workflow problems and drivers. Furthermore, concept design processes have been investigated and analysed and a Conceptual Design Stages Protocol was developed to guide design teams through the feasibility stages. The Protocol was further supported by an Information Technology environment for concept design; a design software applicable to a Tangible User Interface has been developed for benefitting multidisciplinary design teams from the haptic and visual experience, which is substantial for externalising, communicating and sharing ideas among them.

Three different multidisciplinary studies were undertaken that tested both the current paradigm of concept stages and the proposed Conceptual Design Stages Protocol together with the computational design tool. Based on these results a number of conclusions were drawn, with the most important ones being the promotion of cognitive and conceptual activities due to the organised approach supported from the Conceptual Design Stages Protocol, the maturity of the concept ideas owning to the multidisciplinary approach and the importance of technology for promoting collaborative design and bridging different professional viewpoints.

Overall, the research provided a deep understanding of the concept stage design processes and the effect of technology on design activities and it contributed in providing an enabling context for pre Building Information Modelling collaboration; hence, the research has the potential to improve the final design solutions for buildings, by making it possible for multidisciplinary teams to work collaboratively and to involve stakeholders more effectively at the early stages of the design process.

1 Introduction

Information and Communication Technology (ICT) is nowadays fundamental to effective collaborative design especially in the Architecture, Engineering and Construction and Facility Management (AEC/FM) industry. Tools implemented for collaborative design, especially those related to Building Information Models (BIMs), assist and promote effective collaboration between different AEC professionals at all the different design stages. The current paradigm in AEC industry together with BIM implementation has been the outcome of three important leaps in the industry; first of all, the computational technologies that affect not only daily life but also the means and mediums for work, procurement and design. Secondly, the shift of paradigm observed in design and architecture due to the application of these computational tools and thirdly the market requirements for efficiency and waste reduction within design and construction of built environment projects.

The technological evolution of visualisation methods and computational modelling techniques together with a higher degree of complexity in the use of representation means contributed to the transformation of the design process and led to the development of contemporary architectural paradigm (Tierney 2007; Carpo 2013). New dynamic conceptions of space design emerge along with new categories of experiences, due to the accelerating changes in technology (Braham 2008). Buildings' design representations have shifted their influence from the drafting mediums and material properties that defined architectural drawings for centuries to computational design and new methods for machining and constructing. Additionally, the new communication means, including the Internet and wireless technologies of communication, augmented reality, pervasive and ubiquitous computing provide the ground for a more active stakeholders' participation and interaction (Whyte 2004), together with an enhanced requirement for more efficient multidisciplinary collaboration.

Moreover, the computational tools become enablers for market pressure on the application of simulations for AEC projects (Froese 2010). The purpose of simulations is to reproduce as nearly as possible real world experiences and projects, thus allowing close predictions of design, construction and use of the project (Levitt 2012). Waste and cost reduction are key drivers for projects' simulation since the industry has been plagued with costs overruns due to problems with designs and project management (Aouad, Lee et al. 2006). As a result, BIM encompasses the potential for simulating the life cycle of a project including constructability, costs analysis, design and construction scheduling, thus making it essential to apply this technology for providing better design solutions within a collaborative context.

The concept of collaboration within the design of built environment projects is interrelated with the computational design representations since the successful completion of design involves input from a range of AEC professionals that focus on the forms, materials, construction and life-cycle of a project. Effective communication is a prerequisite for the application of BIM and accessible ICT technologies along with visual processes are able to bridge the designers, engineers and users/clients' differences. Furthermore, interactive media, Virtual or Augmented Reality (VR, AR) and phone or tablet (i.e. I Pad) design applications, are only but a few possible means to bring technology closer to the end-users for design communication purposes. As a result, end-users can actually participate and collaborate with the architects/designers during the design procedure by using experimental platforms to provide input for the design proposals.

1.1 ICT and AEC Industry

Three major eras have been identified within the ICT and the AEC field (Froese 2005). The first era dates back forty years and it includes the development of stand-alone software programs such as Computer Aided Design (CAD) programs, analysis and presentation tools. The rapid growth of the internet and other communication tools have catalysed the development of the second era which focuses on computer supported files exchange through emails, the web and Document Management Systems (DMSs). The second era is still evolving as the computational tools improve the speed of the analysis and more complicated types of software are required to tackle the increased demand for analysis and visualisation tools. The third era, which is currently under development, embraces all the different types of software into one common platform and merges the multidisciplinary teams' work into one file, the Industry Foundation Classes (IFCs). The BIM types of software, which utilise IFCs for data structuring, are not based on the layers design method like the CAD tools but on relationships among objects and with other external parameters and values (Russel, Elger 2008). Eventually, the shift of paradigm regards the transition from files exchange to analysis and methods exchange, which results into sufficient control over the building information and moves us from the strictly technological and procedural focus to ubiquitous, multidisciplinary and informational collaboration.

Effective collaboration between the different AEC professionals is a key issue for both the second and the third era. The ICT tools available so far defined and determined the third era and these tools include technologies like BIM, IFCs, virtual design and construction, augmented reality visualisations, like the BIMx platform by Graphisoft (GRAPHISOFT BIMx) and implementation of cloud computing for sharing IFCs like the Gteam group (GTeam). The technological aspect defines the distributed and multidisciplinary environment where the project team members join their efforts to produce computer based virtual models. Adding to that, collaborative design is about participants' relations and they can be enhanced by the mobile, ubiquitous and smart technologies (Horvath 2012).

BIM is the current state of the art regarding the AEC industry, when it comes to bridging design and construction teams within a digital platform and is also the answer to problems of continuity and smooth transition between the different design stages (Egan 1998), from the conceptual design phases, to the detailed designs, construction designs, up to construction itself and covering the whole life-cycle of the building. BIM adoption in practice though is a challenging issue in respect to the product, processes and people, especially regarding the current paradigm in the AEC domain (Gu, London 2010).

1.2 Aims and Objectives

Early design stages' workflow problems occur due to the fragmentation between preparation stage (appraisal and design brief) and design stage (concept, design development and technical design), (Sinclair 2012). With the application of BIM, it becomes even more important to establish a smooth transition from the moment of handling a design brief to building up the design team and the team members' interrelations, for the purpose of creating an enabling collaborative environment.

The early design stages are the most vital for the development of the building design and the decisions taken during these steps are significant for the further progress of the design project, regarding aspects like cost, performance, reliability, sustainability and project's life cycle (Hsu, Liu 2000). Early stages design decisions affect the later phases of design development and any drawbacks occurring during the later stages require huge costs in order to compensate or to correct the shortcomings of the early design stages (Wang, Shen et al. 2002; HOK Chief Executive Officer Patrick MacLeamy, FAIA). Therefore, the necessity for increased effort during the early design stages is a prerequisite for effective overall design and construction stages. Shift of the effort towards the early and conceptual design stages leads to fewer problems with the later design steps and the most important requirement is the effective collaboration between the different professionals.

Following the context description, it becomes apparent that it is a challenge to create an enabling environment for a decision framework, which incorporates the technical tools and the functional requirements and needs together with qualitative issues, and eventually integrates the qualitative data of the early design stages to the later stages of the design process. Bringing the stakeholders together as early as possible could be complicated but at the same time it brings important benefits to the design process (Harty, Laing 2011). The complex aspects are focused on communication, collaboration and coordination issues that could be overcome by utilising effective management, clear specifications for the involved professionals especially with regard to authorship, quality of deliverables and level of details, and also by implementing the described protocol with certain steps and expected outcomes during each stage. Risk management and issues of trust are also encompassed within this process and only a shift of paradigm in designers and contractors mind-set could effectively deal with this problem.

The proposed research is focused on bridging the initial and conceptual design ideas with the further development of the project through multidisciplinary collaboration, which incorporates the maximum of the involved professionals' ideas, including clients, designers and end-users. The reason behind the collaborative design is to maintain the quality of the conceptual ideas throughout the initial design BIM stages and soft landings. Computer-mediated collaborative environments, tangible interfaces, and cloud computing platforms are types of media that promote the Human-Computer Interaction (HCI) and that are tested and utilised for achieving a smoother translation of the ideas into digital information and for overcoming the spatial and temporal barrier through the cloud technologies.

The application of different types of methods (physical and digital) during these processes intends to achieve a continuum between the initial model and the BIM files, which cannot be accomplished with the so far practice. Methods followed by the designers can be either physical, like usage of pen and paper, models, prototypes and sketches or digital, like 3D models, digital sketches and 2D CAD drawings. Traditional drawings and sketches are able to provide the abstraction of information required for the development of the initial ideas and the innovation processes, in contrast to the digital aspects that provide specific information on dimensions and forms and limit the generation of ideas. The ideal current paradigm is about the leap between these two stages and the ideas generation and creativity (Salman 2011).

The research target was focused on constructing a pre-defined design protocol, or as described within the thesis, a Conceptual Stages Design Protocol (CDSP). This protocol included aspects like multidisciplinary team building, design management and predefined steps for the early design stages process. The protocol's integration within the BIM software aimed at smoothing the transition from the initial ideas to the actual model, dealing effectively with the ideas clash, bridging the gap as early as possible between the different stakeholders, like the designers architects, engineers and FM managers, and minimising the iterative loops at later and more advanced design stages thus leading to reduced design iterations while achieving savings both in cost and time.

The primary research aim/question is:

> With a focus in the AEC industry, can computer mediation assist and create an environment for conceptual collaborative design? Furthermore, can we support this process with a design protocol with fixed stages for a more efficient and effective conceptual design?

The research aim was afterward divided into three objectives:

Objective 1:

- **Undertake a review of the current paradigm of conceptual collaborative design in the AEC industry.**

The first aim's objective encompasses an extensive literature review on the topics of the current paradigm in AEC industry regarding BIM and multidisciplinary teams and on collaborative and conceptual design, regarding obstacles and enablers to both of them. Furthermore, the first aim extends into identifying the gap of knowledge, the topics that the research is investigating and the hypotheses to be tested.

Objective 2:

- **Develop and optimise a Conceptual Design Stages Protocol for collaboration during the early and conceptual design stages using digital design and collaborative tools.**

The second aim focuses on investigating the methods and processes for conceptual design both from the AEC industry and from other relevant disciplines like engineering and design. According to that knowledge and based on the research question, a Conceptual Design Stages Protocol (CDSP) is established for AEC design teams to follow during the feasibility and pre-BIM stages. Furthermore, the computational aspect of the research involves the development of a computational design tool applied on Tangible User Interfaces for the purpose to support the Conceptual Design Stages Protocol with ICT implementation and achieve a smoother integration of concept stages with BIM.

Objective 3:

- **Facilitate and test both the current paradigm of conceptual design and the proposed Conceptual Design Stages Protocol, and undertake a critical comparison between the two.**

The third objective incorporates a number of different topics that are analysed in a number of chapters and, for that purpose, the third objective is further subdivided into the following tasks:

a. Review relevant methodologies for investigating design processes and determine the methods to be applied during the studies.

b. Investigate the problems currently faced during concept stages within the AEC industry through interviews and meetings' shadowing with senior AEC professionals to further support the research focus.

c. Undertake three studies during which the current paradigm of concept stages, the proposed Conceptual Design Stages Protocol and computational design tool are tested.

d. Compare and contrast the results from the studies regarding the processes; the current paradigm and the conceptual design stages protocol.

e. Compare and contrast the application of the current paradigm of design mediums and the Tangible User Interfaces for conceptual brainstorming.

The Conceptual Design Stages Protocol was tested and proved according to the research aim, which was to provide a process for effective collaboration during concept design stages. Additionally, computer mediation further supported this process by delivering an enabling environment for conceptual collaborative design. Information gathered through the three studies provided the quantitative and the qualitative data for evaluating the research aim.

1.2.1 Thesis Structure

The thesis structure is developed according to the objectives of the research. Therefore, the thesis initiates with an introduction on the key elements of the research (chapter 1), followed by the first objective, the identification of the research gap as described in chapter 2. An inductive (bottom-up) method is applied for answering this first objective. An extensive literature review contributes to finding the research area and to identifying the gap in knowledge and the research question. The research hypotheses are developed, which are tested, analysed and commented in greater detail in the forthcoming chapters. Qualitative data described in chapter 5 aim to reinforce the research hypotheses in relation to industry requirements, as collected from interviews and design and construction teams' shadowing.

The second objective of the thesis is based on the knowledge and research hypotheses developed with the completion of the first objective. Chapter 3 describes this objective and it includes the development of a Conceptual Design Stages Protocol and of a computational design tool applicable to Tangible User Interfaces. Inductive approach is also utilised for building up theories and research hypotheses from the literature review and prior knowledge (Miles, Huberman et al. 2013), for answering the second objective as described in chapter 3.

Chapter 4 introduces the data collection methodology and the relevant chapters (5-9) that they are all tackling the third objective of the research. The overall research methodology is described in chapter 4, which follows the literature review and research tools development (chapters 1-3). Afterwards, a deductive (top-down) method for data collection and analysis is applied for the third objective of the thesis, as described in Chapters 5-9. Deduction is the preferred method for conducting the three studies and for testing and evaluating the developed theories and hypotheses (Schaeken, Vooght et al. 1999).

The research in its totality is a highly iterative process with the studies' results constantly refining the developed theories. The concepts of inductive and deductive approaches are depicted in Figure 1.1 and 1.2 while the chapters' description is illustrated in Table 1.1 according to the thesis objectives. Importantly, the timeline of the research is presented in Figure 1.3 with the different activities grouped according to the research objectives. Chapter 4 presents a more detailed Table (4.1) focused solely on the third objective of the thesis and its development across chapters 4-9.

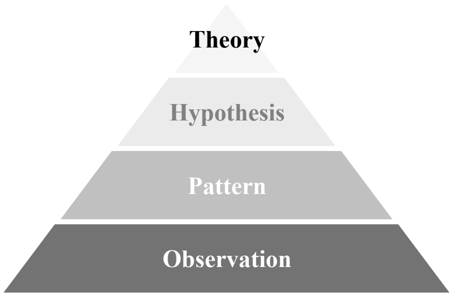


Figure 1.1 Inductive approach for completing the first thesis objective

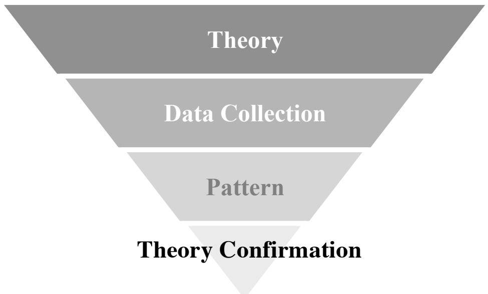


Figure 1.2 Deductive approach for completing the second and third thesis objectives

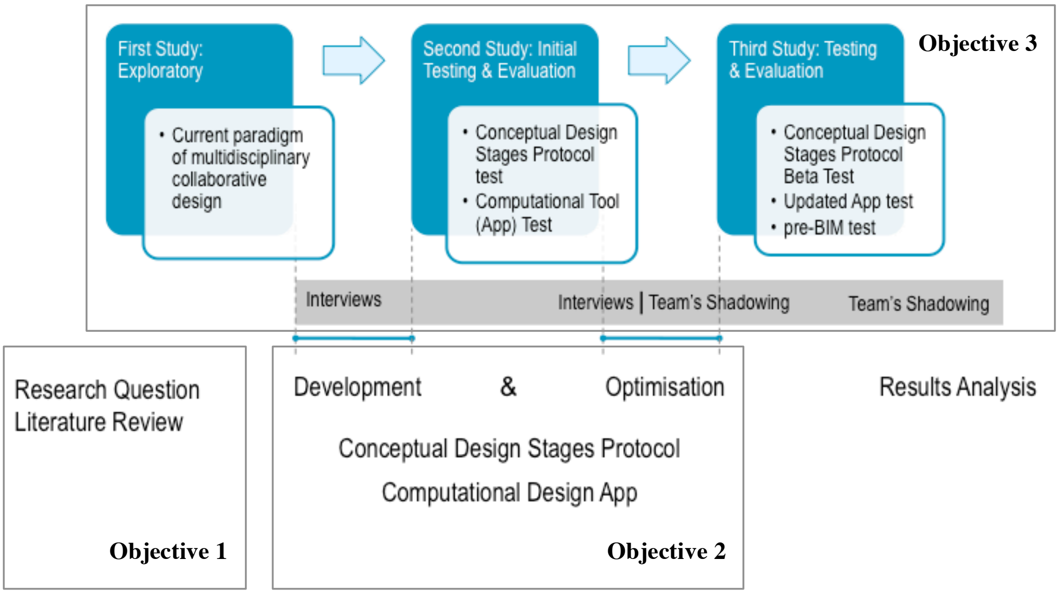


Figure 1.3 Research timeline in relation to the development of the research objectives

Table 1.1 Chapters' summary

Chapter	Description	Objective
Chapter 1	The first chapter provides a brief description of the key points of the research; it introduces the research aim and states the objectives.	
Chapter 2	The second chapter focuses on the reasons for undertaking the research. An extensive literature review describes the setting of the research and the identification of knowledge gaps is materialised together with the focus of the research development.	**Objective 1**
Chapter 3	During the third chapter, the detailed development of the Conceptual Design Stages Protocol is described, together with relevant influences. Additionally, the computational design tool development and implementation is portrayed.	**Objective 2**
Chapter 4	An extensive review of the methodological approaches and the employed methods is discussed within chapter 4. Furthermore, the methodological basis for the following chapters is set. The conditions of the studies and the methods for analysing the outcomes are thoroughly described.	**Objective 3a.**
Chapter 5	Input from interviews and construction and design teams shadowing is presented in this chapter.	**Objective 3b.**
Chapter 6	The first exploratory study is analysed in Chapter 6, during which the current paradigm of conceptual design is monitored. The study's results are presented in different levels of analysis and statistical results showcase its performance.	**Objective 3c.**
Chapter 7	Chapter 7 describes the second study, where the initial testing of the Conceptual Design Stages Protocol and the developed computational tool takes place. Similarly to the previous Chapter, a detailed analysis in multiple layers takes place.	**Objective 3c.**

Chapter	Description	Objective
Chapter 8	This Chapter tests the updated Conceptual Design Stages Protocol and the improved computational design tool. The results of the third study are afterwards described.	**Objective 3c.**
Chapter 9	Chapter 9 incorporates a comprehensive comparison of the three studies regarding the followed process and the use of design mediums and computational media, along with further discussion on the studies.	**Objective 3d. & 3e.**
Chapter 10	The final chapter describes the conclusions of the research and the answers to the aim and objectives of the thesis. Moreover, this chapter provides further suggestions for future research.	
References	The complete list of references found in the thesis is provided according to Harvard referencing system.	
Appendices	Additional materials supporting the research are attached in the appendices. These include copies of questionnaires, of the design briefs for every study, design processes charts and additional material whenever mentioned in the thesis text. Furthermore, a list of selected publications is also attached in the final appendix.	

2 Literature Review

The second chapter of the thesis reviews a number of different topics related to the development of the research context and question and identifies the gap in knowledge and the potential for development, thus answering the **first objective** of the thesis. These topics are interrelated and they form a loop, initiating from the industry context regarding BIM and multidisciplinary teams to collaborative and conceptual design, concluding with computer mediation and technology, therefore going back to the beginning and to BIM. The dual focus of the research is on design process and computer mediation, as illustrated in Figure 2.1. The chapter as a whole covers a range of topics as illustrated in Figure 2.2.

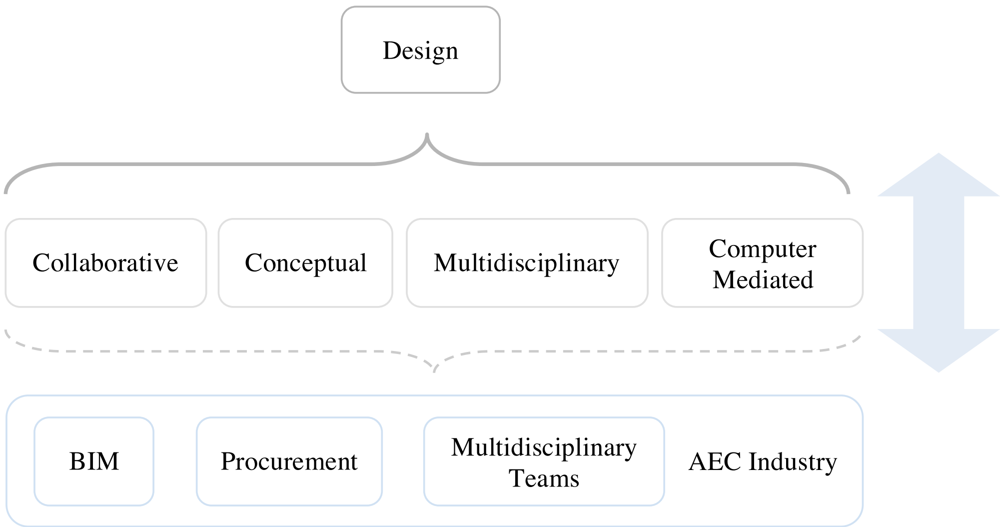


Figure 2.1 Chapter 2 structure

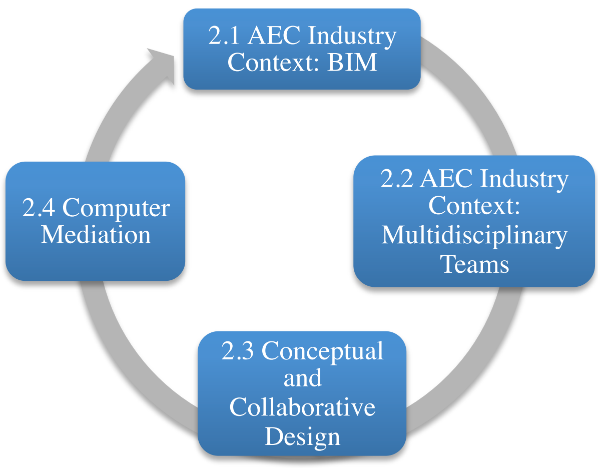


Figure 2.2 Chapter 2 sections

2.1 AEC Industry Context: BIM

2.1.1 Building Information Modelling (BIM)

Collaboration and evolutionally approaches to a project of the AEC industry within a BIM context is a pressing matter due to the 2016 deadline for BIM application to the public sector buildings (Philp February 2012). BIM is an ICT approach including all relevant information for buildings' life-cycle before the actual construction (Gu, London 2010). The included information is both quantitative and qualitative and it allows the AEC and FM professionals to foresee possible issues and problems that might arise during later and more advanced stages of design and construction. Industry Foundation Classes (IFCs) are the types of files utilised and the shift of paradigm, compared to traditional CAD files, lies in the connections and parameters between the built environment elements while working on a 3D virtual environment.

BIM is changing the way we collaborate; it is shifting the focus from the chain of activities to efficient collaboration and to innovative ways of creating, sharing and collecting relevant information among different but project related disciplines. "The tangible benefits of BIM will not come from doing "business as usual more efficiently", they will come from changing the way we work together" (Lockley 2011). Through this collaboration enhanced quantitative and qualitative outcomes are expected that provide greater efficiency, functionality and perspective to the project together with better investigated, wider based and well-reasoned design solutions. While design projects are considered as "scheduled chains of activities which result in design delivery or actual physical buildings as end products of the project" (Penttila 2009), BIM contains the potential for a holistic approach to design projects and decision making for waste avoidance.

Different types of software are nowadays available for the AEC/FM professionals, with the most recent developments including Autodesk's Revit (Revise-It). Revit's innovation is lying in the types of connections between the components, the 3D objects that construct the virtual building, thus the structure, walls, floors, windows and doors, furniture and mechanical, electrical and plumbing facilities. The context-driven parameters, which define the software, update the families associations and they are eventually capable of altering the parts of the building associated with any changes in the building components (Jungreis, Lauer 2011). Other types of software include Graphisoft's ArchiCAD (Graphisoft BIMx), Tekla Structures by Tekla, NavisWorks by Autodesk (Autodesk) that is suitable for controlling and viewing the BIM models, MicroStation by Bentley Systems, GTeam by Gehry Technologies (GTeam), VectorWorks, RhinoBIM, IntelliCAD and many more. A classification of BIM technologies according to their functions is provided by Kassem et al. (2014), with different types of software identified for project programming, including software like M.S. Excel and Newforma, and for design and analysis, thus entailing software like Revit, ArchiCAD, Ecotect and 3Ds Max among others. Additional software suitable for project management and review include FM Systems, AutoCAD and Bentley View. BIM platforms and servers are able to facilitate types of software appropriate to the full range of AEC professionals (Jungreis, Lauer 2011; Singh, Gu et al. 2011) and eventually they benefit the project's life-cycle by promoting a coordinated approach to the design and the construction phases and linking tightly these two stages together. There is no restriction for utilising only one type of BIM software as AEC/FM professionals have different tools but the design coordination can occur by importing all the different files into one platform for coordination, which has to be updated by the relevant professionals (Henrich 2013). Protocols and procedures determined by the types of procurement can be adapted to the available 'off the shelf' software.

2.1.2 BIM Processes

British Standards have been promoting effective collaboration within computer mediation, a process that was initiated by Egan Report (1998) and continued with the second report, Accelerating Change (Egan 2008). In addition to these reports, the British Standards 1192:2007 (BS 1192:2007 January 2008), the successor of BS 1192:1998, is the 'Code of Practice' for CAD and includes information on BIM workflows and levels of adoption (Figure 2.3), still lacking though the coordination and the accuracy between the different work stages, file formats and the new software. More recent BIM standards include BS1192-4:2014, for collaborative production of information, Publicly Available Specifications (PAS) 1192-3:2013 and PAS1192-2:2013 for operational phases, specifications on information management for the delivery phase and collaborative production of architectural, engineering and construction information. BIM Task Force and BIM Task Group is the UK Government Construction Strategy for BIM adoption, level 2, by 2016, which is supported by the BIM regional hubs, the BIM 2050 group, the Building SMARTUK, the International Alliance for Interoperability (IAI) and the Construction Industry Council. Prominent examples of similar initiatives are also being developed in Australia, from the Australian Institute of Architects (BIM in Australia December 2010) and the United States with the National BIM Standards (National Institute of Building Sciences building SMART Alliance).

The drivers for BIM adoption include issues of AEC industry reform, of minimising carbon emissions, of cost reduction and innovation and, eventualy, of improved value for money. The reform is based on fully collaborative processes starting from the early and conceptual design stages up to facilities management and buildings' life cycle. Technology developments are also vital for this transition and, similarly, 3D CAD and data modelling adoption curves by design teams were largely based on the available computer advances (Froese 2010). The adoption curve of 2D CAD was much slower than the BIM adoption and the main reason is that computers processing power is comparatively much better nowadays than in the past while cloud technologies further support information sharing. The technology is now at a stage where barriers are mostly social and perceptual rather than technical.

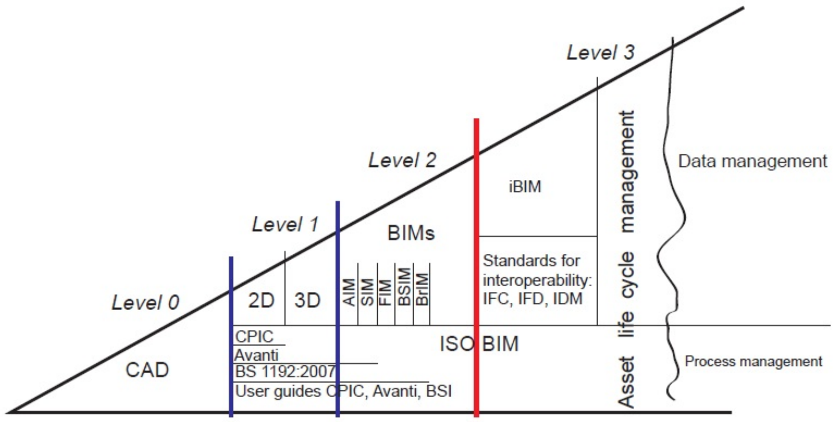


Figure 2.3: BIM workflow and levels of adoption (Bew and Richards, 2008 as in Sinclair 2012)

In addition to BIM, there is the Construction Operations Building Information Exchange (COBie) and Construction Design and Management (CDM) for sharing information about construction. COBie is a system for organising and sharing information between the different stakeholders (clients, designers and contractors) and the specific type of files are utilised for timely delivery of the project's stages and for documenting and grouping buildings components information. Data drops and deliverables are also part of the COBie process with five drops being stated by the regulations, starting from the requirements and constraints, to the outline solution, construction information, operations and maintenance and post-occupancy evaluation (*COBie Data Drops, Structure, users & examples*. 2012; East 2013). CDM 2007 concerns the legal obligations of the construction stakeholders, it distinguishes the duties between the clients, designers and contractors, it ensures the competency of the involved professionals and it includes information about the relevant Health and Safety procedures (The Construction Design and Management Regulations 20072010).

2.1.3 BIM and Conceptual Design Stages

According to the Royal Institute Of British Architects (RIBA) BIM overlay to the plan of work, BIM is not utilised during the preparation and design brief stages, but during these stages the input and output information of the BIM model is defined, together with the desired outcomes and the post occupancy evaluation (first soft landing). Afterwards, the first soft landing leads to the first data drop according to Construction Operations Building Information Exchange (COBIE BIM Task Group 2012). During the conceptual stage, the information from the first data drop is implemented and an initial model is developed for strategic analysis (Sinclair 2012). The initial model is turned into a parametric model (when focusing on the form or during form-finding investigations) or into a model comprised of parametric objects and elements (i.e. slabs, columns, M&E equipment and facades). Afterwards, it is transformed into a BIM model and issues about access to this model through cloud BIM are resolved, leading to the second data drop, with the design development and the technical design following.

2.2 AEC Industry Context: Multidisciplinary Teams

The AEC design teams are considered as facilitators between design projects and end-users or clients and their role is focused on combining complex and different elements and aspects into a coherent and harmonious entirety (Foque, Lammineur 1995; Nilsson, Peterson et al. 2011). Different levels of complexity can define a built environment project from the early stages of conceptual design. These different levels of complexity are composed of objective descriptions of the physical space and of experiential subjective users' space, which thus constitute the specific context of the design process. What is more, the objective design criteria are necessary to be aligned with subjective factors defined by the multidisciplinary approach, like space for electrical and mechanical equipment, specific material finishes, available budget, health and safety issues. As a result, complexity arises from the requirement to merge the different and often contradicting ideas and perspectives of the design solution, from managing large amounts of information associated with the design solution and from understanding the consequences of design decisions for the project's evolution and construction. Eventually, the aim of the multidisciplinary design teams is to merge the conflicting elements into a consistent whole with interrelated parts.

2.2.1 Multidisciplinary Design Teams

Due to the multidisciplinary nature of the AEC projects, it becomes difficult to predict the evolution of a project when observed from individual professional perspectives, an approach though that is considered to be mainstream within the industry, thus leading to fragmentation of the processes and knowledge. Multidisciplinary design teams in the AEC/FM industry are comprised of different professionals who combine their skills, knowledge, expertise and effort for designing infrastructure and buildings models (Kalay 2004). These participants are required to exchange information and take decisions through an interdependent method by communicating ideas, drawings, plans and drafts, and other relevant documentation, while the process of the project is additionally dependant on the individual effort form the participants. As a result, a successful completion of the design covers information regarding the projects' requirements, the specifications of the project itself, like geometry, materials, manufacturing processes and the whole life-cycle of the project, (Klein, Sayama et al. 2003), and it is a highly iterative process with a great number of turn backs for refining designs and plans.

Common problems arising during all the stages of the project are about the tight deadlines, high technology means, matters of interrelations between the participants, communication issues and establishing a common ground of understanding (Cross, Clayburn Cross 1995; Hales 1993) along with issues occurring when professionals with different background, scientific terminologies and experiences meet together to collaborate (Busby 2001). The behavioural parameter is an additional issue to the collaboration processes between the multidisciplinary design teams and, as a result, the design process is critically affected by issues of communication, social processes, negotiation and reflection (Stempfle, Badke-Schaub 2002; Stumpf, McDonnell 2002).

The design team is usually comprised out of an architect, a structural or civil engineer, a quantity surveyor, a project manager, electrical or mechanical engineer, and many other professionals relevant to the type of the project. The greater the scale of project the more complicated it is and a greater number of engineers and different types of professionals are required for a successful completion of the project. Furthermore, city planners and building control officers may affect the design decisions, since legislation controls certain aspects of buildings, like thermal insulation and fire prevention (Emmit, Yeomans 2008). The role of contractors can also influence the design specifications due to the products selection process, which is a common practice for financial reasons (i.e. choosing materials that are more cost efficient). The fragmentation of the industry occurs due to the different types of professionals, since each discipline has developed its own communication norms and knowledge, thus leading to the symmetry of ignorance (Rittel 1984).

The plethora of disciplines together with the fragmentation of the AEC industry intensifies the problems in communication between the different stakeholders and the project team members and communication management becomes a necessity for successful project management (Dainty, Moore et al. 2006). High performance teams occur when effective communication takes place between the team members.

2.2.2 Procurement Models

Procurement models determine the detailed project team's structure (Commission for Architecture and the Built Environment and the Office of Government Commerce 2011) and the delivery relationships between the stakeholders, involving clients, engineers, designers and contractors (Farrington, Lysons 2012). Procurement strategy is essential during the early stages since it calculates and establishes the shared risks between the team members (client or owner, design consultants and project managers) within the project's life cycle, especially regarding time of completion and speed, average or certain cost and quality of the project (Constructing Excellence Limited 2004). Three main types of procurement strategies involve the Design-Bid-Build (DBB) or traditional one, the Design-Build (DB) and the Construction Management (CM), and they are accordingly depicted in Figure 2.4 a., b. and c. The traditional method includes the client appointing the designers to prepare the designs and the tender documents, followed by the contractors and an agreed cost of the project, with the designers acting as an in-between within the clients and the contractors. The DB strategy includes the clients and the contractors, with the second ones being appointed by the first ones; the design is already developed but in some cases contractors need to consult the design consultants again. The CM approach is about the clients appointing contractors, having the construction manager handling the process on behalf of the client, starting from the design to the delivery of the built project.

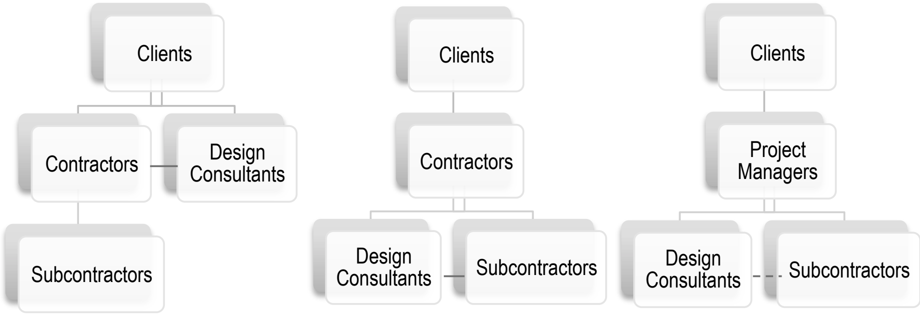


Figure 2.4: Types of procurement

a) Design-Bid-Build b) Design – Build c) Construction Management

Procurement process and planning together with the relative team structure is unique for every project, it depends on the type of the project and it is essential to be established during the early project stages. E-procurement and organisation of the information by utilising web-based forms applied within BIM enriches the quality of information provided, it does not restrict it to geometrical characteristics but it allows incorporation of physical characteristics, costs, quantities and technical specifications (Kymmell 2008). In order to achieve this richness of information, connections with outside sources and files with information are necessary, such as spread-sheets, databases, texts and other form of design software. Furthermore, effective communication and collaboration between the stakeholders regarding their responsibilities and tasks they need to complete require that software is interoperable, especially when it comes to composite models created in different types of software with asynchronous communication (Grilo, Jardim-Goncalves 2011). An additional demand deriving from e-procurement is about the standardisation of the building components products (windows, doors, tiles, mechanical and other installations) and the way they are applied within BIM models.

Private Finance Initiative (PFI) and Public Private Partnership (PPP) types of procurement are also often met in larger public infrastructure projects (Bing, Akintoye et al. 2005). Relationships management among the client and the private consultants and among the different involved consultancies in PFI and PPP cases is essential to be based firstly on trust and confidence (Latham 1994; Egan 1998), and secondly on "strategic and tactical consideration" (Smyth, Edkins 2007). Contractual clauses tend to be more complicated than the DBB types of projects, thus affecting the relationships among the involved stakeholders. Relationship management in these cases contains analysis, investment and value estimation on professional relationships (Bourne 2009). Due to these difficulties it becomes even more important to adopt and foster collaborative working "that goes beyond reactive behavioural adjustment to new procurement conditions" that provide "a shift from relational contracting to proactive relationship management principles" (Smyth, Edkins 2007).

2.2.3 Integrated Project Delivery

Integrated Project Delivery (IPD) or Lean Project Delivery (LPD) is "a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harness the talents and insights of all project participants to optimise project results, increase value to the owner, reduce waste, and maximise efficiency through all phases of design fabrication and construction. IPD principles can be applied to a variety of contractual arrangements and IPD teams can include members well beyond the basic triad of owner, architect, and contractor. In all cases, integrated projects are uniquely distinguished by highly effective collaboration among the owner, the prime designer, and the prime constructor, commencing at early design and continuing through to project handover" (AIA 2007). IPD is also differentiated due to different contractual approaches, legislations, and thus team processes (Mihic, Sertic et al. 2014). IPD also involves risk and rewards sharing among stakeholders together with additional incentives and reductions in constructions costs and facilities management, thus avoiding project delays and reducing waste (DeBernard 2008).

Consequently, IPD encapsulates the BIM long-term potential for incorporating domain technologies, processes and policies (Succar 2009). Early collaboration in particular has the potential under the right conditions to straightforwardly "address the problem of industry fragmentation between design and construction professionals that results in inefficient work practices and costly changes late in the construction phase" (Becerik -Gerber, Des et al. 2014). Importantly, technological tools are not required for early collaboration and BIM can greatly increase the collaboration efficiency through all stages from conception to construction and delivery.

2.2.4 Group Development and Communication

According to Kreps (1989) and as identified by Dainty, Moore et al. (2006) and Emmitt and Gorse (2003), communication is classified in four different levels, with a progressive involvement of people. The first level is focused on the intrapersonal communication that occurs within the individuals as a process of interpreting information. The second level is the interpersonal communication between two people to establish relationships. The third level involves small-group communication with more than two people communicating and coordinating their activities, while the final level encompasses multi-group communication with different teams communicating. All these levels occur during communications within AEC industry, within multidisciplinary teams and among different project stakeholders, from designers to engineers, clients, contractors and clients. These communications are not isolated but they happen simultaneously in most real-world situations, thus making them even more susceptible to problems.

The interdisciplinary nature of AEC project teams is such that in most cases they involve people from different companies and consultancies and with varied professional backgrounds coming together to collaborate for the duration of each project (Dainty, Moore et al. 2006). The fragmentation of the AEC industry is not helping though this 'coming together' and the teams' formations especially for the short durations for projects development.

Good examples of groups' formations within the industry developed during the project evolution in a way that makes best use of participants' capabilities (Emmitt, Gorse 2003). Although the existence of difficulties and barriers in developing team working, during these good examples participants can manage to engage in socio-emotional interactions. Group solving of design questions and design brief demands within the appointed time scales advances the relations among multidisciplinary teams, participants become more confident, trust develops among them and the strengths and weaknesses within the teams are identified, thus working becomes more effective. A model that identifies team and group development as a process defined by four different stages according to Tuckman (1965) and also presented from Emmitt and Gorse (2003) and Dainty Moore et al. (2006) is presented in Table 2.1 and Figure 2.5. The teams' development begins with the forming process, during which members are becoming aware of the project details and they familiarise themselves with their colleagues, followed by the storming one, where participants feel comfortable within the group to exchange their ideas and opinions. Afterwards, the norming process follows where the roles and responsibilities are clear and group cohesion occurs. The final part is the performing when the norms have been developed and effective working takes place.

Table 2.1 Steps for teams' formation according to Tuckman (1965)

	Forming	Storming	Norming	Performing
Action oriented aspects	• Learning about the challenges and the opportunities • Agreement on the goals • Information about the project, the issues and the team • Directions coming from the facilitators or the managers	• Intragroup conflict • Problems' identification • Clash of ideas	• Agreeing on one common and shared goal, actual beginning of collaboration • Identification of the roles and responsibilities	• Effective communication • Team's efficiency • Processes for effective working are in place
Psychological aspects	• Members familiarise themselves with each other • Exchange of personal information • Initial problems faced in an dependable way	• Members' confrontation • Resolving of differences • Important: no judgment, supporting an environment of sharing of ideas	• Communication protocols emerge • Group cohesion	• Sharing a common focus, members are motivated and knowledgeable • Members acting inter-dependently

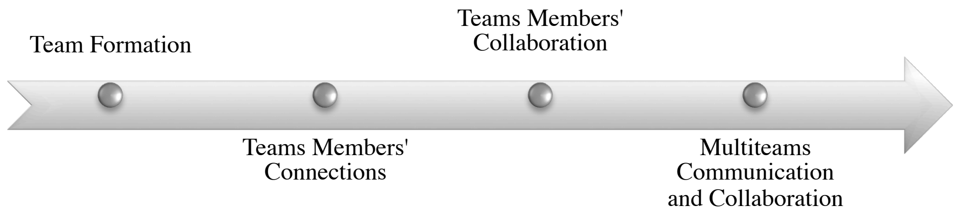


Figure 2.5 Evolution of teams' formation and collaboration

Communication and transfer of information among the different team members during design process evolution in a form of acoustic or visual messages can be represented in a linear way as illustrated in Figure 2.6 (Emmitt, Gorse 2003). Dainty Moore et al. (2006) explain this process that initiates with an input to be communicated. The content of the Input is relevant to the intention of communication, while its source might be any member of the team. The Sender is the person or people sending the Information out, and they are the ones deciding on the content of the message. Often in multidisciplinary teams a number of messages are required to be sent among the members until the context and common understanding of the project is established. The mediums that allow communication, or else channels, are dependant on the type of communication, i.e. for supporting acoustic communication, the channel is air, and for written communication the channel is printed outputs or computer screens. Noise or distortion is characterised anything that can affect the decoding of content. The Receiver is the person or group of people who decode the content of the information sent over through the channels. In order to reach the Output a process is required to be followed by the receiver, that includes the acceptance of the message, its decoding and the translation within the context of the team and project.

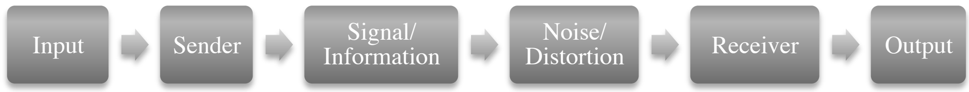


Figure 2.6 Modelling communication process according to Emmitt and Gorse (2003)

2.3 Collaborative and Conceptual Design

2.3.1 Design and Design Process

Design is a process that builds up a description of an artefact, building, process or instrument to meet certain performance criteria and resource limitations; the product is realisable, and satisfies criteria such as testability, manufacturability, and reusability (Tong, Sriram 1992). The design process also might be subject to restrictions, like time, cost and people involved. Design is also ubiquitous therefore generic guidelines for the design process can have great impact.

The essence of design is the communication of information, thus the description of an artefact in a form that is understandable to those who will build it (Cross 2008). The widest form of communicating this information is sketches and drawings that vary in level of details and design scales. The drawings also involve specifications like annotation scales, dimensions and details about the materials. The same process applies to any form of digital fabrication, since the information conveyed in the digital files is once again translated into the form of drawings. The level of details is decided by the efficient construction of the artefact, which could be translated in a backwards process; making cannot start before designing is finished, therefore the design steps can be clearly defined.

Design processes applied for solution finding of design problems often require a co-evolution of the solution and design problem space, in an adaptive and iterative manner. Arguably, solution-finding design processes aim at promoting the evolution and iteration of the potential solutions by taking the stakeholders through actions progression. When it comes to the built environment design problems in particular, they tend to be ill-defined (Rittel, Webber 1973) and various stages of descriptions and representations are required for improved definition and specifications. What is more, heuristics, qualitative and quantitative information are also necessary for describing these problems, leading to a multi-stage, iterative and collaborative process. According to Simon (Simon 1973), the ill-defined design problems require particular design processes that consist out of well-structured sub problems with a retrieval system that constantly alters the problem space by evoking from long-term memory new constraints, sub goals and generators for design alternatives, thus constantly updating the design problem and solution space.

2.3.2 Conceptual Design

Conceptual design is the early design stage during which the abstract solution of the design problem is being researched and the principles of the solution are established. Design questions and issues need to be identified and abstracted for the elaboration of the solution principles (Pahl, Beitz 1995). What is more, preliminary possibilities and concretisation of the project are often required for setting up a working structure. The early design stages include investigations into the general geometrical characteristics, materials, dimensions, ideas about the form and the use of the building. Regarding analogue and digital tools of the design process, sketching is the method that designers mostly utilise during the conceptual design stages. Sketching is essential because it consists of a considerate level of abstraction and of information that can be implemented at later and more advanced design stages (Figure 2.7 and Figure 2.8).

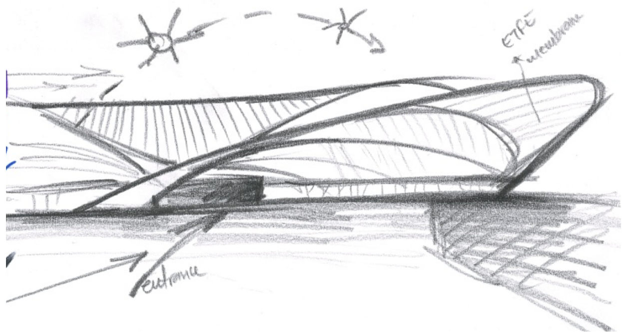


Figure 2.7: Example of a building's conceptual sketch where the form, the materials and the environmental parameters are included (drawn by author)

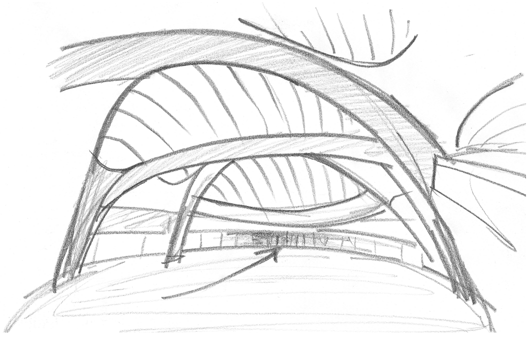


Figure 2.8: Conceptual sketch of the interior space of a building, again the geometry, the structural system are presented (drawn by author)

However, the integration of new media technologies (Aliakseyeu, Martens et al. 2006) within collaboration platforms like BIM can promote the creativity and the high-performance buildings' design. In addition, digital design tools affect the design and thinking process of professionals, together with ways they interact with each other (Yamamoto, Nakakoji 2005). Design tasks are eventually evolved, revised and confirmed by utilising technology and digital tools; hence, leading to intensification of the computer mediated multidisciplinary collaboration (Fischer 2000).

Efficient collaboration during the concept design stages directs smoothly the initial information to the more complicated design and construction stages, thus avoiding unnecessary iterative design loops. Importantly, effective collaboration leads to informed decisions being taken early enough, hence potential problems are predicted and avoided. This can lead to a smooth and informed overall design of a project with fewer iterations being required at more advanced design stages, thus achieving savings both in cost and time. Design iteration, in this case, is the process of repeating working phases where a solution to a design problem is approached step by step until reaching an efficient result (Pahl, Beitz 1995). Iterative loops are always necessary and take place continuously during the design process due to complex interrelationships between the different stages and due to different type of information required from multiple professionals. Although the important role of design iterations, their application between larger stages, i.e. moving from construction design to concept design because of unpredicted problems, is damaging for the progression of the project (HOK Chief Executive Officer Patrick MacLeamy, FAIA). Therefore, a systematic approach and a protocol design are required to limit the iteration loops within predicted processes.

2.3.2.1 Obstacles to Conceptual Design

The early design stages are the most vital for the development of the building design and the decisions taken during these steps are significant for the further progress of the design project, regarding aspects like cost, performance, reliability, sustainability and project's life cycle (Hsu, Liu 2000). Early stages design decisions affect the later phases of design development and any drawbacks occurring during the later stages require huge costs in order to compensate or to correct the shortcomings of the early design stages as represented in Figure 2.9 (Wang, Shen et al. 2002; HOK Chief Executive Officer Patrick MacLeamy, FAIA).

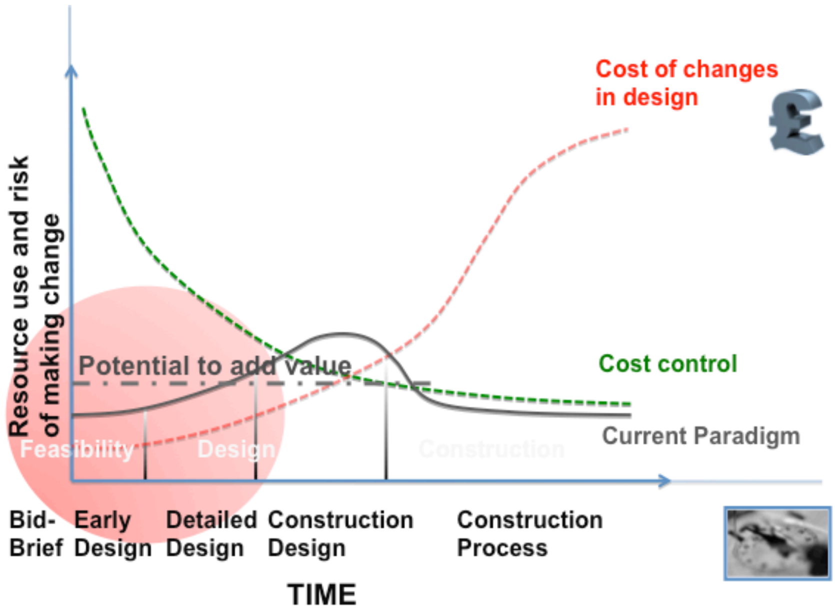


Figure 2.9: Effort-time graph and the relation to the cost curves, adapted from HOK (HOK Chief Executive Officer Patrick MacLeamy, FAIA)

Traditionally, the design effort builds up gradually as design develops, starting with the minimum energy on the programming, problem finding process and conceptual design with the greatest effort provided during the Design Development (DD) and the Construction Drawings and Documents (CDs). Even though during the initial design stages the ability to change the design and actually control the cost is great, as the project develops this ability rapidly decreases and change becomes more difficult. During the design progress the ability to control the construction cost lessens along the progress of the drawings and in case that changes are required during the construction stages the costs can be enormous. Therefore, if the building program and the budget are not clear by the late construction drawings design and documentation stage, failure of the project is inevitable due to huge costs during the construction phase with legal consequences afterwards.

Quite often, delays and costs overruns jeopardise the design and construction stages, especially within AEC Industry (Park, Peña-Mora 2003). Latham Report (1994) claimed that only 70% of projects across UK were delivered within 5% of tender cost and only 38% within 5% of tender program. Megaprojects across the world, with 258 of them in 20 different countries, had cost overruns in 90% of the cases as reported by Flyvbjerg Bruzelius et al. (2003). Redoing parts of the design or work that was incorrectly implemented in the first time is identified as the main reason for these problems (Love, Edwards 2004).

Rework is an occurring problem due to lack of adequate schedule control by design teams, the inability for clients to decide early enough and clashes with technologies and teams' management problems, as reported by McManus, Tishman et al. (1996). Delays and rework are obstacles to the smooth continuum of the conceptual design process, and a more recent publication on the topic that questioned a large number of practices identified as the most important reason for delays to be changes in clients' requirements, needs and wants in planning and early design stages, followed by scope complexity and definition, slow decision making and poor communication and information delivery among professionals (Yang, Wei 2010). Additional reasons for delays included design deficiencies, improper cost estimations, and insufficient training of design teams and unclear authority for control of designs. As a result of these delays, the project deadline has no option but either to move forward or to put pressure to other stages of design and construction (Eggleston 2008), thus endangering the totality of the project and leading to cost and time overruns.

2.3.2.2 Work Stages during the Conceptual Design

Work stages in design can be understood through the application of specific approaches and methodologies. Cognitive sciences and problem solving methodology is essential to be considered, since problem solving need to correspond to the designers' thinking and ideas generation processes (Boden 1991). Systems' theories can also be applied for analysing and optimising complex systems design (Cross 2008; Chestnut 1965; Daenzer 2002); systems' theories describe the general appreciation that complex problems are best tackled in fixed steps, by involving analysis and synthesis in each one of them (Pahl, Beitz 1995).

Defining the design problem and its characteristics is the first step of the systematic approach applied for the conceptual design stages. Problem analysis and clarification of the task are also included into that phase of the process together with information about the system under consideration. The clear formulation of the design obstacle leads to the goals and the intentions setting of the project, which are being clarified at the next step together with the criteria for the subsequent evaluation of the possible solutions as illustrated in Figure 2.10 (Pahl, Beitz 1995). The following stage is the generation of ideas and possible solutions (system synthesis) that are analysed and synthesised according to the information deriving from the previous steps (system analysis). Thereafter, the performance and effectiveness of each solution/variant is appraised (system evaluation) according to the goals that are established in the beginning of the process and the optimum design solution is selected (decision). Finally, if the end design product meets the objectives then the process is terminated and the next stages succeeding the conceptual design are following, including the most detailed design of the project and the construction design; if the resulting conceptual solution is incompatible with the goals of the product then a repetition of the process is required.

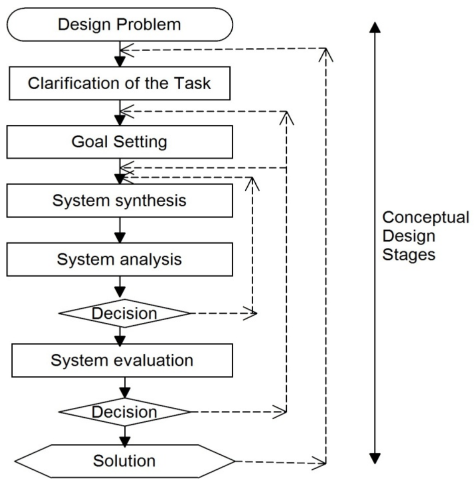


Figure 2.10: Proposed work flow during the conceptual design stage, adapted from Pahl and Beitz (1995)

Within each step of the process, which are considered as operational guidelines for action, the personal thinking process of the designers like creativity and generation of ideas merge with the problem solving steps. Flexibility is also essential for adapting the process and the design solution approach within the design problem's parameters. The designers also need to be informed of the process, the procedural plans, the iterative loops and their position in collaborative design.

The clear steps within the process ensure the connections between the different aspects of objectives, planning, organisation and control and they also clarify the workflow. These aspects define the project and include information on the physical processes and the geometry. As a result, the initial problem confrontation and the definition of the projects' goals and principles lead afterwards to a solution field with multiple possible answers to the initial problem. Furthermore, the methods for reaching this step include both conventional and intuitive methods. The conventional approaches are comprised but not limited to literature research, natural systems research, existing technical systems analysis, and models' tests and the intuitive methods include brainstorming design sessions (Osborn 1979) with multidisciplinary groups of AEC professionals.

2.3.2.3 Sketching as a Design Medium for Conceptual Design

Design is a process that builds up a description of an artefact, building, process or instrument to meet certain performance criteria and resource limitations; the product is realisable, and satisfies criteria such as testability, manufacturability and reusability (Tong, Sriram 1992). The essence of design is the communication of information, thus the description of a design solution or artefact in a form that is understandable to those who will build it (Cross 2008).

Visual communication methods (such as drawings, images, sketches) significantly enhance the quality of information during the design process by providing a representation of the artefact, hence leading to visual engagement of the designers. The design initiates at the conceptual stage during which the initial possibilities of a project are investigated, together with the aims and objectives of the building project, the geometrical characteristics, materials, dimensions, ideas about the form and the use of the artefact/building. The tools that designers use during conceptual design include among others documents, images, maps and sketches. Free-hand drawings consist of a considerate level of abstraction and of information that can be implemented at later and more advanced design stages. Therefore, sketches are the mediums that allow for greatest flexibility, speed and intuitiveness for communicating ideas. Moreover, ideas verbalisation and the use of computers for conceptualising ideas can further enhance the ideation process, foster new patterns and relationships and result in additional ways of perceiving and conceiving design solutions (Jonson 2005).

Sketching and drawing are "spatial and haptic exercises that fuse the external reality of space and matter, and the internal reality of perception, thought and mental imagery into singular and dialectic entities" (Pallasmaa 2009), pp. 89. Sketches are widely considered the most significant way for design ideation, especially during conceptual design stages, that visually engages the designers and effectively represents the artefact. Free-hand sketches by using pen and paper, together with physical models are the preferable media used by designers (Pallasmaa 2009; Schön 1991; Cross 1999; Gross, Yi-Luen 1996), while nowadays digital representations are also an additional tool for form generation processes (Sass, Oxman 2006; Burry, Burry 2012). Designers often find difficult to describe non-verbal processes in words (Darke 1979) and sketching allows for further communication of ideas.

2.3.3 Collaborative Design

'Collaborative design' of the built environment is a design process comprised out of a set of parameters (Klein, Sayama et al. 2003) with two or more stakeholders or participants working together to achieve a shared goal (Loren G. 1995). Nowadays, the increased complexity of built environment projects demands strong interdependencies among design decisions and different types of stakeholders, hence making it challenging for deciding on one finalised design that satisfies the often contradicting involved parties during the lifecycle of a project (Figure 2.11). Collaborative design depends on a set of parameters or issues it aims to solve according to the project's requirements and relevant specifications. Collaborative design also encompasses information about geometrical characteristics, measurements, technical details and the manufacturing processes, during the whole life cycle of the project, starting from project's design brief and appraisal, the concept and the design development, the construction details and drawings, the construction itself and the post-construction stages with the actual use of the building and the FM (Sinclair 2012). Due to the ill-defined nature of the design problems though, they are considered "moving targets" that quite frequently do not have a solution but only a resolution (Arias 1995), and the multiple stakeholders involved in this process lead to changes, conflicts and adaptations. In many different cases, collaboration aims to achieve an informed compromise among the collaborative parties, rather than consensus (Fischer 2000).

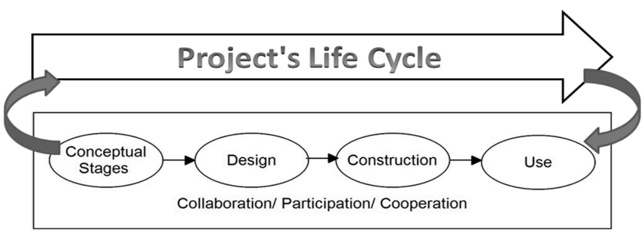


Figure 2.11: Project's life cycle within all the design stages and also within the context of collaboration, participation and cooperation

During good examples of collaborative design of complex projects, the dominant activity among participants is to teach and instruct each other since the levels of complexity are quite advanced and require specialised knowledge; often though, communication breakdowns occur due to different cultures, thus diverse norms of representing ideas (Snow 1993). The symmetry of ignorance, as defined by Rittel (1984), is “the assumption that the expertise is distributed as well as the ignorance about the problem; that both are distributed over all participants, and that nobody has any justification in claiming his knowledge to be superior to anybody else’s” (Rittel 1984), pp.324- 325. As a result, the maximum participation is required to generate the greatest amount of information and knowledge.

Furthermore, to support collaborative design Rittel (1984) identified a number of principles, and these include the argumentative structure of a planning process and its inspection as a network of issues with positives and negatives. Additionally, deciding on different aspects of a project is also part of this process for taking design decisions, with the essential prerequisite that they evolve with an advancing comprehensiveness and that the utilised arguments are transparent to avoid judgemental decisions. A consequence of the previous statement is also the objectification for listing the most important requirements of a project and the stimulation of doubt, with the first one making sure that all the required aspects of a project are taken through the solution and the second one encouraging the expression of objectives for solving the differences as soon as possible. Eventually, the different viewpoints supported with collaborative design can promote the research of design alternatives and potentials and allow the discovery of implicit knowledge and ideas.

2.3.4 Obstacles to Collaborative Design

Quite often collaborative design is plagued by “heavy reliance on expensive and time consuming processes, poor incorporation of some important design concerns (typically later life-cycle issues such as environmental impact), as well as reduced creativity due to the tendency to incrementally modify known successful designs rather than explore radically different and potential superior ones” (Klein, Sayama et al. 2003), pp.201.

Obstacles that may appear during the collaborative design process are issues of workflow, education and different design and engineering backgrounds of the professionals, technological challenges arising with different types of software, team working, cost and responsibility (Randy 2011). These issues occurring during the complex design problems can be further sorted out according to spatial, temporal, conceptual and technological barriers (Fischer 2000). The spatial barrier refers to different geographical and spatial locations of the participants which can actually be overcome by addressing the temporal barrier; regarding the temporal barrier and asynchronous communication, it can be tackled by both computer-mediated communication (CMC) and face-to-face (F2F) communication, with effective emotions communication in both cases (Derks, Fischer et al. 2008). Moreover, the conceptual barrier is about education obstacles and the various terminologies utilised by the different AEC professionals whereas a common ground and shared understanding is required for harmonic communication. Finally, the technological barrier is about issues that arise with software mismatches between different users/ professionals (Orlikowski 1992) and about human-computer collaboration problems especially with methods of achieving it, either by endowing computers with human-like abilities or by having computers complementing humans (Loren G. 1995). Further details on the technological barriers and issues are presented in Section 2.4.

Due to the ambiguity of the conceptual design stages, it is essential to make a clear focus of the issues that arise during this stage, to categorise the obstacles according to the design aspects and to additionally acknowledge potential enablers of that process.

2.3.4.1 Errors during Collaborative Design

Regarding the conceptual barrier, quite often misunderstandings and failures of cognition distribution lead to problems and errors within teams and projects. Errors limit a task's performance and can be costly; on the other hand errors have potentials of informing about problems within organisations, they promote learning by making professionals adapt to changes and they can reveal issues within processes that were considered standardised (Busby 2001). Errors can arise from the interactions between members of design teams, professionals and the use of technological tools and professionals and formal organisation, as reported by Busby (Busby 2001).

These errors among professional interactions occur due to a failure to involve relevant professional bodies, informing about problematic situations and effects of different design actions and verifying decisions. Additional reasons include lack of project's scope definition and strategies information according to the involved stakeholders, and lack of understanding in the design processes among different professionals. The failures that appear when professionals interact with design representations involve misuse of design features and conventions, lack of suitable review of the designs, problems with use of appropriate software, lack of relevant guidance for occasional users and no feedback for adapting software use according to issues previously occurred. What is more, errors that are the result of interactions between professionals and organisations/practices or with external environment might result due to incorrect work allocation and due to mistakes with work conventions for the required activities. The absence of suitable professionals for tackling the appropriate design problems and of notification mechanisms for changes in plans and designs can also lead to errors and mistakes. Eventually, complications with involved professionals on their relevant task goals combined with lack of planned synchronisation are also potential problems for prompting errors during design processes.

2.3.4.2 Conflicts during Collaborative Design

Collaborative design encompasses both technical characteristics and socio-technical dynamics and interactions that affect its progress, due to its cooperative nature (Lu, Cai et al. 2000). Objectification is not always achieved; neither is decisions transparency and removal of judgmental elements among team members, thus resulting in conflicts among team members. Conflicts within a team undertaking a project of the built environment could be a rather expensive issue, since it can potentially lead to delays and/or terminations of collaborations, a costly problem of the AEC industry (Vaaland 2004). High costs for changing partners and apprehension of clauses within contracts for legal sanctions are additional consequences of conflicts. Subsequently, effective conflicts management is essential during collaborative design and the clash of ideas can actually promote ideas generation, especially during the early design stages.

Conflict management can achieve insight and information among the involved parties regarding the core of the project; it can create a cooperative context between the participants and re-build the relationships on a new constructive basis by bridging the gaps between the different perceptions of the involved stakeholders (Vaaland 2004). The ways that can be achieved incorporate identification of conflictual events and transparent analysis of different perceptual ideas about the project. Conflicts management initiates with the identification of the issues that led to the conflicts, either by interviewing the different participants or by data resources, while conflicts can be interpreted according to perceptions and processes of the involved sides (Vaaland, Håkansson 2003). The next step would initiate with assessing these differences in opinions according to project's governance mechanisms, which are case dependant and might include among others mechanisms of incentives, authority and trust. These mechanisms could also be comprised of formal aspects like contracts, official and unofficial agreements, patterns of behaviour, organisational procedures and informal aspects like trust and ease of adaptation depending on the conflict.

Effective project management and task completion within Engineering, Construction and Procurement (EPC) firms in particular, requires a number of competencies such as entrepreneurial, technical, evaluative and relational ones (Lampel 2001), which can eventually lead to overcoming the obstacles to project partnering and collaboration. The entrepreneurial aspect refers to detecting and developing opportunities while the technical competencies refer to the technological proficiency and to the ease of software use. Furthermore, the evaluative aspects of competency are about the total cost of the project organised in data-sheets and workbooks. Finally, the relational competencies are comprised of the effective management of all the stakeholders (from the designers, engineers, to the clients, suppliers and contractors) and the required adjustments of the teams' dynamics.

2.3.4.3 Team Building

Team building comprises an additional significant feature for conflict management and successful collaboration during the early design and partnering process (Larson 1997). During these sessions, the key projects' stakeholders are involved in activities for reinforcing individuals' interaction, for sharing goals for collective action and for setting tasks' interdependence (Loo 2003). Innovation during team building could occur according to four factors, including vision and clear objectives, equality and safety in participation, task orientation and support for innovation (Anderson, West 1998). Symmetry of ignorance can additionally promote learning by sharing understanding (Snow 1993) and by utilising distributed cognition and mutual competency (Fischer 2000) in order to maintain the collaborative work developed during the team building processes; for example, joint evaluation during the project's process, the set up of rules for resolving problems (Larson 1997) and optimal selection procedures.

2.3.4.4 Participatory Design

Built environment projects are required to provide people with a range of social and environmental values that fit their needs since it is the end users that will benefit from them and, hence, they define the quality of the end product. The ideal sustainable built environment project would allow the access to and transfer of information between natural and social systems interactions (Scott, Bakker et al. 2012). Participatory and community design is a movement based on the principle that if the end-users affected by the project are actively participating in the project creation and management then the end-product will answer in a more effective way to their needs and requirements (Sanoff 2000), thus enhancing collaborative design. Participatory design includes information exchange, conflicts management and design; it also minimises the anonymity of the users and it includes an active involvement of the end-users to the decision-making processes. Community participation is based on the context and the requirements of the project and the aim is to raise awareness of the end-users, to assist them perceive the final project and its consequences to their lives and to promote participation into the decision making processes.

In most conventional projects, little feedback from the end users and the social systems is available prior to completion of the project. Community members, agencies, and design relevant people are usually included in the review and assessment of land and resource policies and planning proposals, yet the clients/ end-users and professionals are not in a position to fully understand the consequences of the choices made, like the potential impacts of changing land use, the landscape and the quality of life (Salter, Campbell et al. 2009) or to communicate their ideas in a way that specialists can find useful. The people who are eventually related to the design process are the designers together with planners and the clients, both of which groups being active participants with the last ones deciding the scope of possible decisions even before the first ones (Sanoff 2000). However, the actual users together with the rest of the community are included in the building codes and regulations so as to automate the design process without eventually reflecting and answering to particular projects' sustainability and community needs. Furthermore, a necessity for an empathetic approach to design is also acknowledged, since design teams face not only functional requirements but also supra-functional, including social, emotional, cultural, and aspirational needs and wishes (Malins, McDonagh 2008). As a result, participatory and collaborative design practiced in design teams can promote implicit and non-verbal considerations as stirred from user-centred design approaches.

2.4 Computer Mediation for Collaborative and Conceptual Design

2.4.1 From CAD to Ubiquitous Computing

The rapid evolution in computing systems and different types of technology related to communications, visualisations and interactions led to what is considered the fourth industrial revolution or digital revolution (Acs, Groot et al. 2002). This revolution was focused on information, thus placing it in the centre of attention as an asset. It also affected the ways with people interact with information, hence the replacing of paper based recordings by digital ones, the ease of access to information and the different types of information visualisations. Furthermore, the availability of digital storage space together with the speed of information processing and the networks' capabilities of connecting over geographic boundaries, (Horváth, Vroom 2015), strengthened digital presence at communication, work and every aspect of everyday life. This process influenced CAD development and it was triggered by the technological advances, starting from the early 1960s (Okada 1999). Research during that period was focused not only at representations of geometric design but also on interactive input and output methods.

A second period of evolution in CAD systems took place from the 1970s to 1980s, during which the CAD tools were established and marketed (Eaglesham 1979) while attention was given to interactive workstations. Furthermore, a CAD framework was introduced for reducing drafting times. The diversification of CAD systems happened straight after, with a range of analysing tools being developed. A number of factors promoted CAD integration among designers, including the technology breakthrough to the wide use personal computers, the necessity for self-contained CAD stations and the methodological integration of these systems within the development of a project (Eastman 1991). Increased sophistication in the development of CAD tools led to the period around the end of 2000-2010 decade, with advances in visualisations, immersive virtual reality technologies for post-processing designs and sharing of information in a collaborative manner either offline or online. The latest period until nowadays is bringing methodological intensifications of various tools and applications domains, utilising the so far developed computational tools (Astroth 2008). CAD is further applied in biomedical sectors and in molecular scale (Sun, Starly et al. 2005). A representation of the phases of CAD development is illustrated in Figure 2.12.

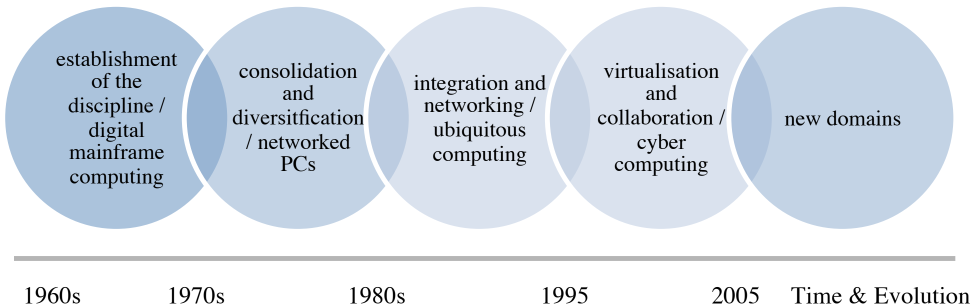


Figure 2.12 CAD evolution, adapted from Horváth, Vroom (2015), pp. 163 and 166.

The strive for moving beyond desktop computing and for allowing design teams interacting with other types of information, such as text, audio, video and drawings, is interwoven with the CAD and technology development (Trivedi, Sagar 2010). The development of Ubiquitous Computing (UbiComp) is the method "for enhancing computer use by making many computers available throughout the physical environment by making them effectively invincible to the user" (Weiser 1993). UbiComp aimed at incorporating a great variety of data transfer through ceasing the barriers between technological artefacts and every day life. Although UbiComp potentials, the relevant applications face obstacles related to the use of these systems and according to relevance, usability and context awareness. Further problems also arise due to networking, acquiring access to them, managing the produced data and ensuring security. Finally, there is not enough information regarding the impact of these systems to the users cognitive actions (Lyytinen, Yoo et al. 2004).

UbiComp can be applied through a range of hardware and software that take advantage of different inputs to interact with, like the use of senses for controlling, actuating and deducing, in combination with the digital aspects of the tools, like visualising, computing and communication of information. Furthermore, UbiComp can be embedded in various means; it can be part of wearable technology, of mobile computing technology, like on smart surfaces, and it can be incorporated in ambient environments (Sharples, Jeffery et al. 2002; Beale 2007).

Smart surfaces are the environments in particular that promote the interactions with both the users and the digital environments. Both implicit and explicit interfaces apply for ubiquitous computing, including hand written and sketching interfaces, motion and gestures inputs, voice recognition, on-screen recognitions and interactions. More recent developments involve hybrid interfacing technologies combining a range from the previous interfaces with brain-computer controls (Sivanathan, Lim et al. 2015).

2.4.2 Graphic User Interface Systems

Graphic User Interface (GUI) systems are the mainstream approach for utilising CAD systems through interfaces that allow users' interactions with the different types of software through graphic buttons. Certain mediums are utilised for translating users intentions to these 2D screen representations, such as a mouse, a keyboard or a design tablet. Various applications of these systems for conceptual design purposes have been observed. These include 3D design systems that vary in their approaches and are comprised among others out of voxel objects' systems, like the Virtual Lego system that utilises 3D Lego blocks where participants can create and manipulate the blocks through a GUI input (Oh, Stuerzlinger June 2004). Difficulties occur within the particular system though, focused on the size of the basic voxels and the lack of more complicated shapes. DDDoolz is also an architecture voxel tool that aims to assist design in the early design stages with basic 3D models (Achten, De Vries et al. 2000). The users add, remove or group basic 3D blocks. Further systems utilise the Window, Icon, Menu, Pointer (WIMP) paradigm for allowing freehand sketches to be translated into models (Olsen, Samavati et al. 2009). The sketch-based interfaces either utilise pen devices or mouse input and the sketches are afterwards filtered, smoothed and beautified. SKETCH (Zeleznik, Herndon et al. 2006) is such an example of a gesture-based interface where GUI systems are the input devices and the free-hand design is rapidly transformed into simplistic 3D scenes. The main disadvantage of SKETCH though is the limited number of possible gesture combinations and the necessity for users' training. The Electronic Cocktail Napkin program (Gross 1996) supports not only collaboration but also freehand drawing input for making and recognition of diagrams and Digital Clay (Schweikardt, Gross 2000) applies machine vision for transforming sketches into 3D design. 3D conceptual design systems also include SESAME, which is a set of guidelines for computer-based 3D conceptual design via 2D drawing interface and additional design actions like extrusion and sculpting (Oh, Stuerzlinger et al. 2006).

Computer mediation has also been utilised for filter-based collaboration model, during which the semantically rich and domain specific information has been categorised according to the different disciplines involved in a project (Lee, Jeong 2012). As a result, participants are able to retrieve relevant representations from a database by creating specific queries and they can additionally monitor the design developments of other participants by adopting the relevant professional filters. The target of that project was to achieve increased understanding among participants by enabling sharing of information.

Approaches for next generation CAD systems propose four different features, including cognitive design techniques, supporting collaborative design, conceptual and creative design; furthermore, natural systems can also provide inspiration for applying these characteristics (Goel, Vattam et al. 2012). During the particular case, a system called Design by Analogy to Nature Engine (DANE) is utilised for providing information about possible answers to conceptual design questions. The answers are organised within a database and reflect biologically inspired design solutions. Pictorial and symbolic methods of representation feed into the design process facilitation and provide the participants with a range of tools for them to use (Chandrasegaran, Ramani et al. 2013).

Eventually, the Computer-Supported Cooperative Work (CSCW) is a rather wide range of systems that support workflow and business process management (van der Aalst

2007). These systems can further be categorised according to space and time taxonomy and the application level taxonomy (A. Ellis, Gibbs et al. 1991), with the first one applied for synchronous and asynchronous collaborations, while the second one organises systems according to their purpose. Production workflow systems focus on the processes and not on the flow of information (Aalst, Hee 2002). Further systems include email providers, like Outlook, or systems that incorporate both data and processes.

That type of systems can embrace three different types of interactions with the users, including viewing data, exchanging and exploring them and as a result can included spaces for production, coordination and communication (Isenberg, Elmqvist et al. 2011). CSCW systems are applicable for the AEC industry by connecting building elements and schedules, communication among collaborators and advanced data visualisations. The application of CSCW systems for the built environment showcases examples within BIM implementation, for promoting 4D simulations and therefore collaboration (Boton, Kubicki et al. 2013). The software produced progression graphs could be adapted based on the needs of different multidisciplinary participants and according to the shared data on the BIM model. Eventually, CSCW and its computational methodology aims at filtering the business requirements according to the professionals, hence allowing layers of adapted representations and of information.

2.4.3 Mixed Reality

Technology evolution enhances human-computer interactions allowing for a continuum between reality and virtuality. Even though the main reason for these developments is the technological advancements, they can still have radical implications for experiencing and interacting with computation. These technologies, whether are embedded or wearable/transferable, promote a transformation and shift the focus from the computing side to the physical one. What is more, the embodied actions of people with the technological mediums result in implications in real-life space experiences (Dourish, Bell 2007). According to Dourish and Bell (2007), space is organised not only because of technology but also due to culture, and that provides a framework to understand and find coherence with the human activities and the design activities especially. New technologies prompt people to reencounter spaces and layer physical and digital activities; the technology though that allows these interactions also requires physical structure and space, for example, the wireless and mobile networks that allow the experience of networks mobility through a physical infrastructure. As a result, "there is already a complex interaction between space, infrastructure, culture and experience" (Dourish, Bell 2007), pp.429, and UbiComp denotes that its goal is not restricted only to computational settings but also the processes through which it can be adapted and experienced.

Tangible User Interfaces are situated between real environments and Augmented Reality (Figure 2.13), they are part of UbiComp technologies and they are comprised out of physical objects that work as interfaces while the computer disappears into the physical workspace. Augmented Reality blends real and virtual elements, by computing data from the real world into the virtual one, like the SmartReality augmented reality app (http://smartreality.co/) that integrates BIM models and paper plans. Virtual Reality users immerse into the virtuality through physical artefacts, like masks in Cave Automatic Virtual Environments (CAVEs).

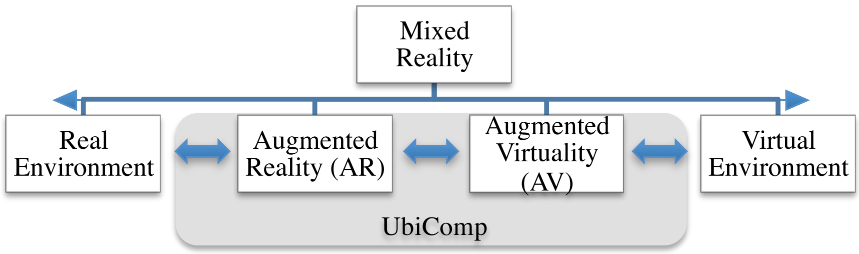


Figure 2.13 Reality- Virtuality (RV) continuum adapted from Milgram and Kishino (1994)

Different types of interfaces for promoting interactions especially within AEC industry have been observed and reported, like 3D collaborative virtual environments, sketch and gesture input, physical interface and immersive and interactive environments of VR (Cheng 2003). VR can assist in the analysis and evaluation of virtual prototypes in a realistic manner and quite often more effectively than physical or visual models (Kan, Duffy et al. 2001).

Computer Supported Collaborative Design (CSCD) has also been developing the last twenty years (Shen, Hao et al. 2008). It aims in addressing increasingly complex designs that require collaborative team working. When it comes to the built environment in particular, CSCW can improve project management and promote the exchange of information across disciplines (Garner, Mann 2003). Human Computer Interaction (HCI) applied for AEC include the use of immersive hardware, like CAVEs, gloves for gesture input, eye tracking and movement tracking. These types of environments and hardware allow the simultaneous participation of multiple team members thus promoting the development of new ideas (Churchill, Snowdon 1998). Furthermore, VR has the potential to assist collaborative and cooperative design by enabling the emergence of participants to the designed worlds (Mobach 2008).

Virtual Worlds (VWs) can further promote collaborative design by implementing computer mediated communication for reviewing designs and for advancing synchronous and asynchronous collaboration in cases where spatial barriers forbid face to face communication (Koutsabasis, Vosinakis et al. 2012). VWs are derived from the evolution and merging of Collaborative Virtual Environments (CVEs), of VR technologies, from a combination of 2D and 3D user interfaces and they are influenced from AR, while they currently describe desktop multi-user persistent 3D environments (Bartle 2003). VWs are comprised of 3D visualisation platforms and they may be utilised for simulation, navigation and control of the virtual environments. Presence and co-presence are also characteristics of these platforms and as a result they can provide the capacity for engaging remote participants and for adding value to AEC conceptual design (Koutsabasis, Vosinakis et al. 2012).

2.5 Summary

Following the literature review, it becomes apparent that a holistic approach to conceptual design, integrating different opinions and professionals, computer media and tactile technologies, organised communication and spaces for ideation, is the knowledge gap that the particular research is aiming to investigate and answer. The necessity for increased effort during the early design stages is a prerequisite for effective overall design and construction stages. Shift of the effort towards the early and conceptual design stages has the potential to lead to fewer problems with the later design steps and the most important requirement is the effective collaboration between the different professionals. Furthermore, analogue sketches during the concept stages are able to provide the abstraction of information required for the development of the initial ideas and the innovation processes, while the digital drawings in advanced design stages provide specific information on dimensions and forms and limit the generation of ideas. A key challenge concerns the leap between these two stages and the consequential ideas generation and creativity.

The method suggested by the research for tackling problems with workflow, education and organisation involves the development of an organised process/ protocol that includes aspects like team building, design management and predefined steps for the early design stages process and that supports the multi-party agreement and early involvement for maximising the potentials of collaboration and coordination for the entirety of a project. Furthermore, the intention to integrate this process within the BIM software promotes a smooth transition from the initial ideas to the actual model for targeting effectively the problems occurring during collaborative design. Furthermore, smooth transition can bridge the gap as early as possible between the different stakeholders, like the design professionals i.e. architects, engineers, FM managers, and can minimise the iterative loops at later and more advanced design stages.

ICT implementation from the concept stages can further support collaborative design and ideas generation methods implemented within emerging augmented reality technologies can be the drivers and enablers for a more efficient collaboration during the early design stages. The learning curve of adapting advanced CAD and CSCW technologies within the AEC industry is quite steep even though governments' incentives put pressure for BIM implementation. Nonetheless, ubiquitous computing and augmented technologies have the potential to make this transition smoother and allow a more hands-on experience for experienced designers, thus simulating processes done with physical means but digitally augmented with additional features. For this purpose, a computational design tool making use of HCI is also proposed during the thesis.

As a result, it becomes essential during the thesis to understand and interpret the impact of Virtual and Augmented Reality (VR and AR) applications to the cognitive and perceptual activities of the designers, and to achieve a smoother integration of technology to the current paradigm of design work in the AEC industry. Bridging the gap between ideas generation during conceptual design and their representation in later and more advanced design stages is about linking the space of ideation with communicating and realising these ideas. Furthermore, supporting users in the conceptual design tasks through smart environments by promoting implicit knowledge and ideas generation through multidisciplinary involvement is also an area investigated during the thesis. This task is even more challenging with the introduction of BIM digital technologies, hence the requirement for digitisation and for computer mediation even from the conceptual stage, in order to achieve a smoother transition between ideas conception and realisation. These computational mediums do not intend to simulate or make design decisions but to assist in the logic of design teams, prompt participants to generate and share information and to arrive at judgements. Eventually, the totality of these conclusions is presented in Table 2.2.

Table 2.2 Obstacles and enablers of collaboration and proposal for a conceptual design stages protocol and for a computational design tool

	Barriers/ Obstacles	Enablers	Suggested methods through this Thesis
Collaboration	Workflow	Information on project governance, design processes and clear strategic scope definition. Synchronisation of involved participants.	Development of a predefined conceptual design stages protocol/ process. Advancing comprehensiveness. Argumentative structure of planning process
	Education	Predefined design features and conventions	Informed decisions and discussions among stakeholders.
	Technology	Guidance when necessary for software implementation, managing conflicts among designs (BIM) Specialised software knowledge	Development of a conceptual design stages computational tool for easier transfer of concept to BIM Non-intrusive technologies for embodied action
	Conflicts	Identification of conflictual events and resolving through predicted steps for mechanisms of reworking	Clear steps for evaluating solutions, thus promoting argumentation and informed compromising/ consensus. Transparent and non-judgemental argumentations. Prioritisation of project requirements. Stimulation of doubt.
	Organisation	Suitable work allocation, notification for work changes	Multidisciplinary teams for promoting design alternatives and potentials and allowing discovery of implicit knowledge.
	Spatial Barriers: different locations of stakeholders	Synchronous and asynchronous communication through computer mediated and face to face communication	Face to face and cloud collaboration

3 Developing the Research Tools

Chapter 3 describes the toolbox of the research according to the second objective of the research:

> Objective 2:
>
> - Establish and optimise a Conceptual Design Stages Protocol for collaboration during the early and conceptual design stages using digital design and collaborative tools.

The chapter initiates with a review of the design processes and a detailed description of the purpose and the development of the predefined Conceptual Design Stages Protocol (CDSP). Afterwards, the development of the computational tool is described; this second part initiates with a review of past and current relevant technologies that combine tangible user interfaces for design purposes followed by the description of the tailor-made computer-mediated application for the requirements of this thesis.

3.1 Design Processes and Protocols: a Review

3.1.1 Design Problem/ Design Brief

Design problems can be related to any design relevant discipline, from M&E to architecture and from product to industrial design. These problems originate either straight from a client or from someone in-between, like a company, consultancy or contractor, and the design problems' requirements and descriptions construct the design brief. Quite often, design problems are considered ill-structured because the brief descriptions are fuzzy with regards to the deign prerequisites, the design goals and the methods to be involved (Simon 1973). The design problems can be 'ill-defined' and 'wicked', in a sense that there are no definitive and objective answers (Rittel, Webber 1973), in contrast to 'tame' problems, developed by science that can be exhaustively formulated. 'Wicked' problems cannot be definitively described since there is an infinite inventory of conceivable solutions. What is more, the design problem representation and description is often ill-defined and various stages are required for improved definition and specifications. Heuristics, qualitative and quantitative information are therefore necessary for describing a problem, leading to a multi-stage, iterative and collaborative process (Chandrasegaran, Ramani et al. 2013).

Ill-defined problems share the same structure with the wicked ones, in a sense there is no definite formulation of the problem, the solution objectives are vague and criteria and constraints are unknown (Tong, Sriram 1992). Furthermore, the problem formulation includes inconsistencies and the formulation of the problem is depended on the solution. The solution ideas provide a way of comprehending the problem and design criteria and constraints influence the problem afterwards, since certain aspects of the design problems can be revealed only by proposing solution ideas. Similar to wicked problems, there is eventually no definitive design solution.

The design process developed in response to ill-defined problems is composed out of well-structured sub problems with a retrieval system that constantly alters the problem space by evoking from long-term memory new constraints, sub goals and generators for design alternatives (Simon 1973). The problem space according to Simon is composed out of goals, constraints and objectives of a project. A recognition mechanism between the problem solver/ designer and the problem space evokes relevant information and knowledge from designers' long-term memory that feeds back into the problem space. This process constitutes a retrieval mechanism between noticing and evoking. However, during the design process, the information retrieval interrupts the continuity of design flow. As a result, a greater number of iteration retrievals are required for allowing the incorporation of a greater number of ideas within the problem space. When the problem space is unchanged then the assimilation of new information from the problem solving mechanisms does not affect the process, since it means that any new information has already been considered and is part of the problem space. What is more, in the case of a problem space that adapts to the new information, provisions are important to be considered for incorporating effectively that information that is coming either from the long term memory, the external environment and the sensory channels or the problem's modifications, as depicted in Figure 3.1.

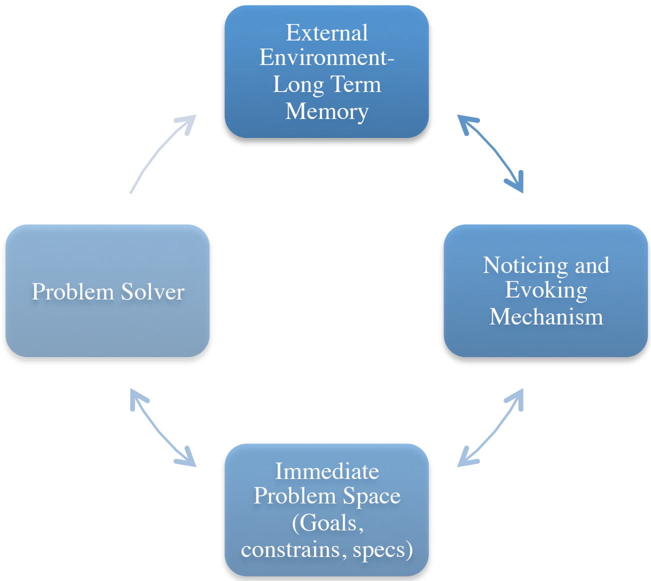


Figure 3.1: System of ill-structured problems showing relationships and feedback links from the retrieval mechanism.

The design problem solving as a simplified process especially for architects starts with the design brief provided by the client to the architect, which includes information on the client's needs, the budget and other vague specifications deriving from the dialogue between the two stakeholders. The design goals remain incomplete and the architect evaluates the requirements and derives specifications from the information provided, like the size of the building. Afterwards, the designer will refer to the list of attributes related to the building's typology, regarding materials, structure or other buildings examples. The actual design process is evolving with the information arriving from memory and from the attributes at any given point and they are the ones that provide the stimuli for the design process to move forward by generating the forthcoming design components. What is more, triggering the design with new imported information can generate design alternatives. The whole design begins to acquire structure by being decomposed into smaller problems, thus leading to well-structured smaller problems but ill-structured bigger ones.

3.1.2 Descriptive Models of Design Protocols

Design processes have been modelled previously according to different perspectives and theories. Descriptive models are the ones that illustrate the steps of the design process as sequences of actions that occur during design. These models tend to identify the importance of the conceptual stage in the beginning of the process, thus focusing on the solution based approach of the design thinking. The initial concepts are afterwards subjected to analysis, evaluation, refinement and development (Cross 2008). If there are problems within this process, feedback loops lead to the generation of new concepts and the design process starts again. The described design process is heuristic, meaning that it builds on the acquired knowledge, and the design problems are ill-defined by nature; therefore there is no definite solution at the end of the design process.

Schön's theories on reflective practice for design practitioners provide the most basic form of design process, which is the four steps of naming, framing, moving and reflecting (Schön 1991). According to Schön, further attention should be focused on the structure of the design task and of linking the different steps of the process together, allowing for an easier flow between them. Schön's theories on reflective practice have also guided research of team design (Valkenburg, Dorst 1998). The theories claim that team based design is episodic and these episodes are categorised into the four aforementioned activities of naming, framing, moving and reflecting/deciding as presented in Figure 3.2 (Schön 1991). According to Schön, not enough attention is given to the structure of design tasks and the crucial problem of linking processes and tasks and the design processes are driven by a kind of knowing which is inherent in intelligent action (Schön 1991). Action-oriented design is proposed and the suitable method for that is the explicit reflection that leads to the development of the conscious decisions and actions (knowing in action) (Rod 2011).

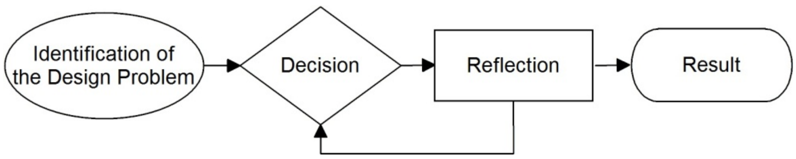


Figure 3.2 Schön's model on reflective practice and the four stages

The design process described is heuristic, meaning that it builds on the acquired knowledge and the problem space adapts to new information inputs. Additionally, the design problems are ill-defined by nature; therefore there is no definite solution at the end of the design process. Engineering systems theory applied within problem solving can be also translated in design steps by dividing the process in fixed stages as described by Pahl and Beitz (Pahl, Beitz 1995). These stages include conceptualising the problem, embodying and detailing the possible solutions, evaluating them and deciding on the suitable one. The engineering perspective of the solution finding and design process includes the division into working and decision making steps, thus ensuring the links between objectives, planning, execution and control (Pahl, Beitz 1995; French 1971; Archer 1984). The key stages from design and engineering disciplines are presented in Table 3.1.

Applying the systems theory within problem solving can be translated by dividing the process in fixed steps as described by Pahl and Beitz (1995). These basic steps include conceptualising, embodying, detailing, evaluating and deciding. The engineering perspective of the solution finding and design process includes the division into working and decision making steps, thus ensuring the links between objectives, planning, execution and control (Pahl, Beitz 1995, Krick 1969, Penny 1970). These links can effectively achieve a generic framework for solutions finding as illustrated in Figure 3.3.

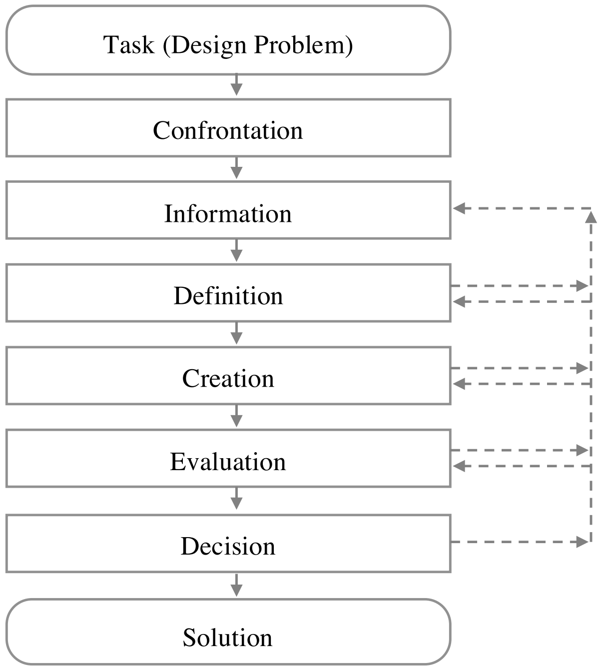


Figure 3.3: General process for solution's finding, pp.63, (Pahl, Beitz 1995)

Table 3.1 Design and engineering field conceptual design processes

Engineering	**Initial Design Stages**						
Schön 1991	Identification of the Design Problem	Decision	Reflection				
Cross 1989/ 2008	Clarify Objectives	Establish Functions	Set Requirements	Determine Characteristics	Generate Alternatives	Evaluate Alternatives	
Pahl and Beitz 1995/ 1988	Design Problem	Clarification of the Task & Goal Setting	System Analysis & Synthesis	Decision	Evaluate System	Decision	Embodiment Design
French 1971	Need	Problem Analysis	Statement of the Problem	Conceptual Design	Selected Schemes		

Table 3.2 Practice focused initial and conceptual design systems

AEC Industry	**Initial Design Stages**			
RIBA Plan of Work 2013	1. Preparation: Project Objectives, Business Case, Feasibility Studies, Assemble Project Team.	2. Concept Design: Outline Design Proposals (Structural, Services, Landscape), Preliminary Cost Planning, Agreement on Project Brief		
PAS 1192-2:2013	Brief	Concept	Definition	Design
COBie Data Drops 2012	Data Drop 1: Requirements and Constraints	Data Drop 2: Outline Solution	Data Drop 3: Construction	
BS 7000: Part 4: 1996, Design Management Systems	Design Brief: Interpretation of the Project Brief, Assigning Responsibilities, Brief Development	Conceptual Design: Outline of the Design Process		
Macmillan, Steele, et al. 2001	Interpret: Specify Business Need, Assess Functional Requirements, Identify Problems	Develop: Develop Functional Requirements, Set key requirements, Determine Project Characteristics	Search for Solutions Transform and Combine Solutions, Select Combinations	Converge: Evaluate and Choose Alternatives, Improve Details

The initial design processes have been modelled according to different perspectives and theories, applied from AEC practice based perspectives (Table 3.2) including Royal Institute of British Architects (RIBA) Plan of Work (Sinclair 2013), Construction Operations Building Information Exchange (COBie) Data Drops (East

2013), British Standards 7000 Part 4 (BS 7000-4:2013). Furthermore, processes coming from design field (Schön 1991; Cross 2008) and from engineering perspectives (Pahl, Beitz 1995; Krick 1969) are illustrated in Table 3.1. According to all these models, the solution space is described as a set of steps or stages, which illustrate the sequences of actions that occur during design. All of the different design processes tend to identify the importance of the conceptual stage in the beginning of the process, thus focusing on the solution based approach of the design thinking. The initial concepts are afterwards subjected to analysis, evaluation, refinement and development (Cross 2008). If there are problems within this process, feedback loops lead to the generation of new concepts and the design process starts again as depicted in Figure 3.3. The latest and most important practice focused design processes are also presented in Table 3.2.

A more recent development in the field of mechanical engineering is related to concurrent engineering processes that promote multiple viewpoints consideration during solution development (Détienne, Martin et al. 2005). Collaborative design further supports this process since the cooperative solutions' space, especially within Computer Supported Cooperative Work (CSCW), supports compromises among professionals, engineers or designers (Bucciarelli 1988), as long as it encompasses relevant information for the project (Cheng 2003). The cooperative awareness information as defined by Chen, Zhao et al. (2015), aims at assisting multidisciplinary collaboration by providing enough information on a project within the digital collaborative platforms through mechanisms that support calls for specific information to avoid information overload.

When it comes to practice focused design processes, British Standards (BS) and professional institutes have been actively promoting effective collaboration through key work stages. RIBA Plan of Work 2013 aims at organising a project's work stages, from setting the strategic definition of a project before the design brief up to the post-occupancy evaluation after the project has been completed. Similarly, PAS 1192-2:2013 specifies the information management by using computational methods, i.e. Building Information Modelling (BIM). These standards guide the information flow from the design brief up to the project's operation. The PAS 1192-2:2013 on Building Information Management (Project information Management, PIM) provides further details of the key gates and the data management within BIM. Predecessors of these guides that provided information on design management and CAD systems implementation include BS 7000-4:1996 on design management systems and BS 1192:2007 respectively (BS 1192:2007 January 2008), which is the 'Code of Practice' for CAD and includes information on BIM design workflows and levels of adoption. The details of the AEC focused design processes are briefly presented in Table 3.2. **Detailed Tables with further concept stages processes are described in Appendix A.**

A generic framework for the AEC industry that goes into further detail is the one developed from Austin, Steele et al. (2001). This research acknowledged the lack of shared understanding during the design activities and suggested that design teams could work better when “in possession of a general programme of events or activities through which they are likely to pass than when no such structuring concept is help” (Macmillan, Steele et al. 2001). This research reviewed a range of relevant existing processes and it was further supported with interviews with design professionals on conceptual design. The steps identified for concept design included interpretation of the project requirements, development of project characteristics, a search for design solutions, followed by transformation of the solutions depending on suitability and convergence for improved results. The detailed steps are presented in Table 3.2

Following the review of the initial design stages according to different guides and standards, it becomes apparent that these applicable especially to the AEC industry are focused on the overall approach to the initial design stages with no detailed steps or processes being provided for a holistic workflow during conceptual design. They try to achieve a generic approach on the types of decisions that have to be accomplished without focusing on how these decisions can be taken. What is more, these standards consider the initial stages of a project as consecutive steps, while in reality design has a strong iterative nature with a great number of stakeholders being involved, both designers and other professionals. Therefore, encompassing enhanced understanding, space for iterations, input from all the involved professionals for informed decision-making and advanced comprehensiveness becomes essential for effectively tackling conceptual design.

3.2 Developing the Conceptual Design Stages Protocol (CDSP)

3.2.1 Development of the Conceptual Design Stages Protocol: Initial Stages

Three main parts of the conceptual design process applied within the AEC Industry have been identified during the research, as illustrated in Table 3.1, 3.2 and Appendix A review. These parts were considered for the formation of an initial version of a conceptual design process as presented in Figure 3.4. These parts included initiating a project by setting the design brief and gathering relevant information, facilitating the brainstorming processes for ideas generation with a number of design iterations occurring at that point and eventually agreeing on the project programme and achieving design verification and the final solution to the design problem. Due to different types of projects complexity, the requirements during all parts depended on procurement approaches, on project delivery methods and on work structuring, but they could still be distilled in these three parts.

The first part is about the design brief and the identification of the problem, pinpointing the clients' needs and objectives, setting up the business case and most importantly concretising the design brief and all its necessary information. The task clarification, which focuses on identifying the objectives and the qualities of the design solution, is followed by setting the task aims and constraints that restrict the solution and allow for further in-depth analysis. The different types of procurement are set together with any contractual processes, which result in calling in the suitable professionals according to their knowledge and the input they can offer to the project.

The first and third parts presented in Figure 3.4 are quite clear in their essence, while the second one that describes a process requires greater detail to be applied for design purposes. The second part concerns the actual brainstorming processes for ideas and concepts' generation. During that part, objectives of the project need to be prioritised, constraints are specified and the first outlines of design proposals are created. Typical constraints applying to most projects include cost, value creation and value for money of the project, lifecycle of the project, aesthetics, ergonomics, timescale, scope and risk assessment and in many cases they are project dependant. The particular part though is considered a 'black box' for the AEC industry (Lawson 2004), with no particular process having been identified as such, apart from Schön's model (1991). The ways that the different professionals are asked to collaborate and contribute to the project are depended on the different consultancies and the project applicable procurement approach, with a lot of problems arising due to this process. These problems are related to lack of an organised method that result into miscommunications among professionals, non-informed decisions inducing design iterations and fragmented workflow. Eventually, the third part focuses on design verification regarding whether the design proposal satisfies the functional and other specifications. The attributes of the proposed solution are examined against the projects constraints and objectives and the client requirements.

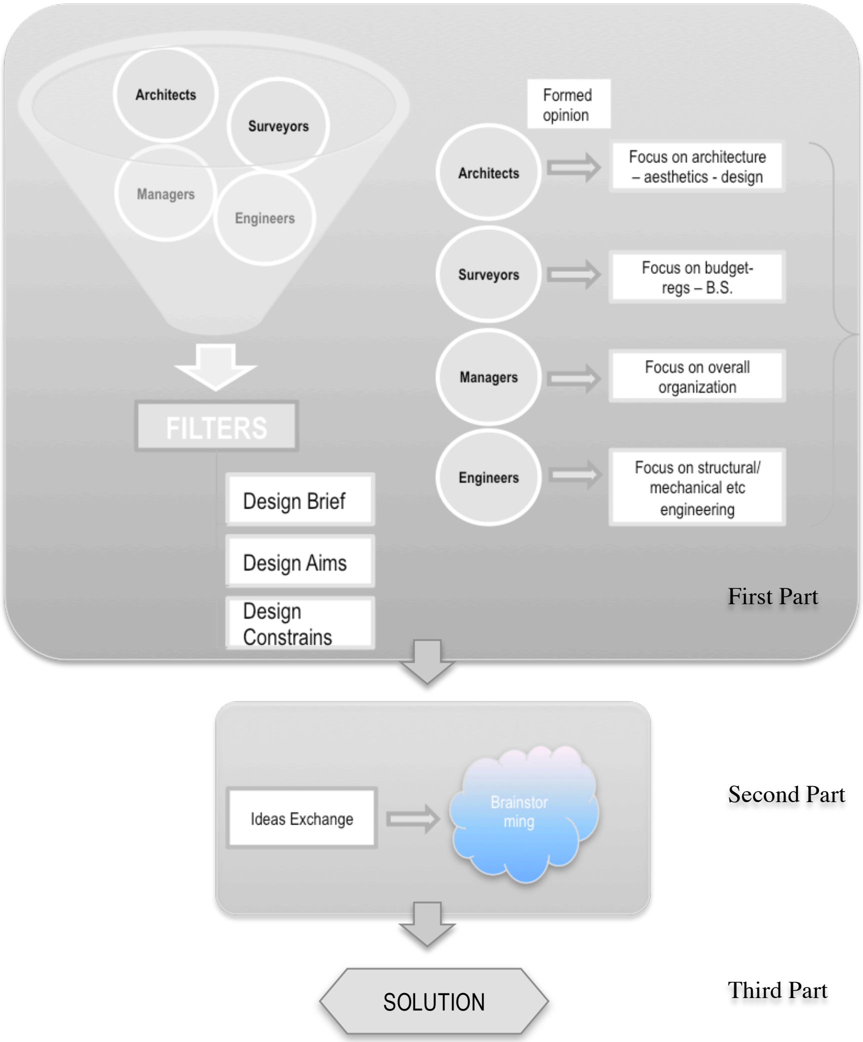


Figure 3.4 Initial research development of design process in three parts

A first approach to merge the three parts with engineering and design systems and to refine them is illustrated in Figure 3.5. The vertical process illustrated in Figure 3.5 is the series of actions described by Pahl and Beitz (1995) regarding conceptual design while the side actions are the initial ideas for the adaptation of the process for the built environment. Then, the process was translated as follows, the design problem is stated and afterwards the task clarification and the design aims and constraints are introduced, the first part of the conceptual design process. A search for solution principles follows, during which the development of the potential ideas and design solutions is realised. Application of ideas generation and brainstorming methods achieve system analysis and synthesis. New ideas are evaluated according to the initial aims and objectives and it is essential to achieve consensus among the design team members, while the process concludes with the achievement of the conceptual design solution.

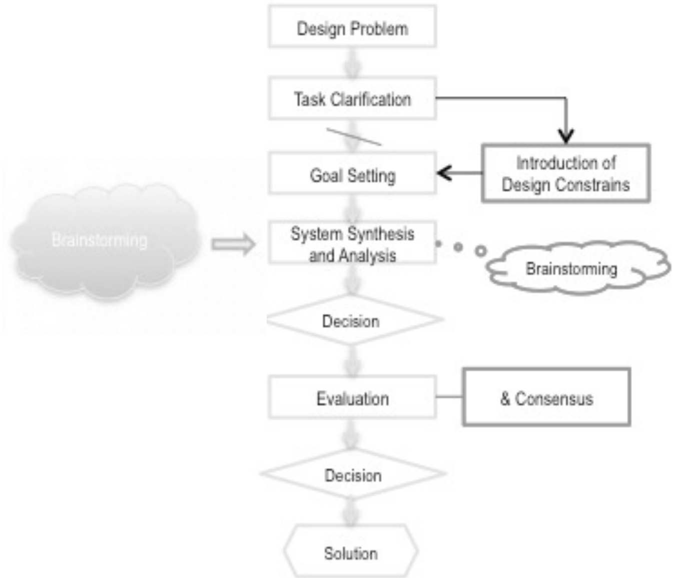


Figure 3.5 Brainstorming process for the AEC Industry

3.2.2 The Developed Conceptual Design Stages Protocol (CDSP)

The design systems considered in Section 3.1.2 and in Appendix A result in proposing a predefined Conceptual Design Stages Protocol, following the lack of an organised system focusing solely on conceptual stages, especially within the built environment industry. Due to different project complexities design processes are generic and provide the key types of decisions and stages that have to be accomplished during each step of the process without identifying how these steps are accomplished. Interestingly, scientists tend to use a certain strategy and a systematic approach for understanding and identifying the rules that could enable the solution generation by utilising analytical methods, as demonstrated in Section 3.1.2, while on the other hand, design professionals focus on initial explorations and then suggest a variety of possible solutions, a methodology of synthesis. In both cases, iteration processes occur in an organised matter for improving the existing knowledge and deciding about the validity of possible solutions according to whether they answer the design questions or not with the improved understanding (Lawson 2005).

Based on that research, a predefined Conceptual Design Stages Protocol has been synthesised, developed and tested during two case studies. The initial model is presented in Figure 3.5 based on the conceptual design process developed by Pahl and Beitz (1995) which was afterwards adapted for the built environment according to the design stages from Cross (2008), Schön (1991), Macmillan, Steele et al. (2001) and RIBA Plan of Works (2013).

3.2.2.1 CDSP description

The construction of a pre-defined descriptive model with structured and linked steps has been developed to support the early conceptual design stages. The steps are divided between working and decision making, for ensuring that the links between objectives, planning, execution and control are made. The developed protocol begins with the formation of the design team and the initial introduction to the brief. It continues with the decision making process that it takes into account the project's constraints and objectives, which is then followed by brainstorming possible design problem solutions and synthesising the information. The protocol is complete when the suggested solutions are evaluated, the design team achieves a consensus and the final design solution is proposed. During this process there are certain decision-making points that act as gates for smooth and continuous solution finding process as depicted in Figure 3.6. **The steps of the Conceptual Design Stages Protocol are numbered for the purpose to reflect the analysis of the studies that are described in chapters 6-9. Section 4.6 provides further details on the analysis according to the mapping of the teams' actions within time. Furthermore, figure 4.17 presents the analysis tool where the numbered steps reflect the process suggested by the Conceptual Design Stages Protocol.**

The Conceptual Design Stages Protocol as a simplified process applied for the built environment, begins with the design brief provided by the client to the AEC professionals, which includes information on the client's needs, the budget and other vague specifications deriving from the dialogue between the stakeholders. The design goals are being set and the relevant AEC professionals evaluate the specifications and derive some further attributes from the information provided, like the size of the building. Afterwards, the designers will refer to that list of attributes related to the building's typology, regarding materials, structure or other buildings examples.

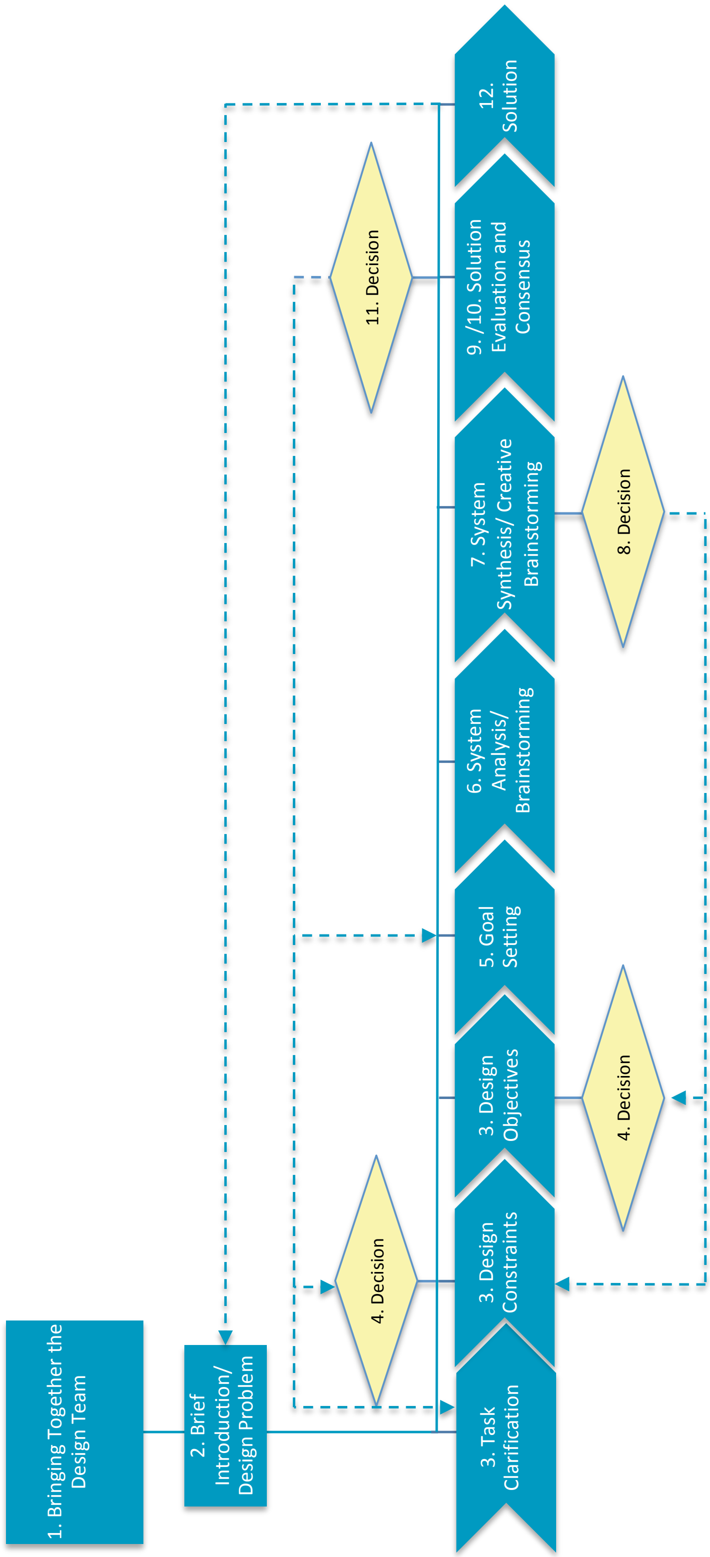


Figure 3.6 The pre-defined Conceptual Design Stages Protocol (CDSP).

The actual design process is evolving with the information arriving from memory and from the attributes at any given point and they are the ones that provide the stimuli for the design process to move forward by generating the forthcoming design components. What is more, design alternatives can be generated by triggering the design with new imported information. The whole design begins to acquire structure by being decomposed into smaller problems, thus leading to well-structured smaller problems but ill-structured bigger ones.

Importantly, the decision points along the process reflect the shared views and agreements among the participants regarding the project. These decisions consist of small milestones within a project collaboration management where the informed consensus between the different disciplines is achieved. Feedback loops allow the reconsideration of the achieved consensus in case this informed compromise does not comply with the design brief requirements, the project objectives and goals. However and due to the application of the CDSP for the feasibility and concept stages within the particular research, the type of professionals involved during the application of the CDSP are restricted to the design team members. The end users' and clients' requirements and viewpoints are described within the brief introduction and the presentation of the design problem while a moderator is the one applying this CDSP within a design team. In order to further adapt this process to the AEC industry, the role of the moderator could be assigned to the design manager or to a "collaboration" manager. Eventually, the end solution achieved at the end of this process represents the product to be published and presented to the clients.

3.2.2.2 CDSP as an adaptable process and the "Collaboration" Manager

The CDSP is highly adaptable and it represents a collaborative design process that could be applied at any point within the different stages of design. Additionally, the type of participants could further adapt according to the type of procurement utilised for a project. The duration of this process and its milestones are not restricted but it could be modified according to the requirements of a project. Regarding the application of the process, it could be facilitated by design, collaboration or project managers and it could easily be integrated within an on going or a new project.

Qualitative data that are presented in chapter 5 regarding interviews with senior AEC professionals and shadowing of design and construction teams, further highlight the problems occurring during design collaborations and emphasise the necessity for a process like the one proposed from the research. The most important emerging patterns of problematic areas included that working in professional silos and having separate solutions for the different type of professionals continues to be a common practice within AEC industry. Consequently, the intense amounts of information exchanged during team meetings could highly benefit from the application of the CDSP that would achieve a smooth integration of design decisions and informed decision-making within the context and the requirements of a project. The CDSP aims to systematically, strategically and efficiently bridge different professional viewpoints and to promote an effective and analytical ideation process.

Moreover, the studies described in the thesis included the researcher being a group moderator for the CDSP application. The moderator was not intervening during the studies, instead, the role was to monitor and ensure that the teams were following the CDSP. Similarly to Harty (2012), who suggests architectural technologists should be embracing the new role of BIM managers, this research is suggesting an additional role for the design teams, the CDSP moderator or else the role of **"collaboration manager"**. For the purpose to further adapt the process to the AEC industry it is important to consider the potential professionals who could embrace this role. CDSP is not dependable on any specific profession; as a result it could be applied from different types of professionals related to project management, design management or professionals that have a deep understanding of the multidisciplinary collaborative teams. BIM is challenging collaborative work; therefore, smooth multidisciplinary collaborative design requires a change not only in culture and mind-set of the design teams, but most importantly, it requires the application of well-structured collaborative processes that are supported from relevant moderators.

3.3 Review of Computer Mediated Design Tools

3.3.1 Tangible User Interfaces

Tangible User Interfaces (TUIs) are able to merge the physical environment and digital worlds (Ishii, Ullmer 1997). TUI is a field within HCI that couples digital information to everyday physical objects and environments and they are classified in three different types, Interactive Surfaces, Coupling of Bits and Atoms, and Ambient Media. TUIs have been extensively used for learning purposes, for programming, problem solving and entertainment (Zuckerman, Gal-Oz 2013), and they are capable of establishing a greater sense of presence in virtual environments due to the visual, auditory and haptic combination (Hecht, Reiner et al. 2006). Integrating information from different sensory modalities results in a richer and more coherent experience that can be applied to co-located collaborative design. TUIs have also the potential to further enhance the cognitive activities by coupling physical artefacts with digital representations, visualisations and information.

The continuing evolution of technology is managing to bridge the gap between Human- Computer Interactions allowing for a seamless and natural exchange between the physical and virtual world. TUIs are situated between real environments and Augmented Reality (AR); they comprise out of physical objects that work as interfaces while the computer disappears into the physical workspace. Design disciplines aim to utilise TUIs to support design processes through tangible interactions. Many different types of applications (apps) have been developed, with most of them based initially on a proof-of-concept approach. A range of apps' prototypes are oriented to provide solutions to more complex design practices, like architectural design, for the reason that tangible environments provide a straight-forward design process by mimicking physical means. Examples of such apps are currently applicable in the market for use on mobile phones, Ipads and tablets and they include options for drawing, like Sketchbook by Autodesk (Autodesk 2015), Adobe Ideas by Adobe (Adobe Creative Cloud 2015), Paper by 53 (53 2015), for scanning or photographing spaces and creating 3D models or large scale images for further processing, like the MagicPlan by Sensopia (Sensopia 2015) and Photosynth by Microsoft (Microsoft 2015). More advanced apps allow viewing of 3D models, like Rhino 3D (Rhino 3D 2015), or inspecting, editing and working on BIM models, such as BIMx by Graphisoft (Graphisoft BIMx 2015) and Autodesk 360 (Autodesk 360 2015). However, the impact of TUIs and any AR or Virtual Reality (VR) apps to the cognitive and perceptual activities of the designers has not been fully explored, together with their implementation to the traditional and current practice workflows.

3.3.2 Applications for the AEC using TUIs

The Electronic Cocktail Napkin (Gross 1996) was a tangible platform that supported synchronous collaboration by utilising digitised pens and papers either for co-located or distant designers (Figure 3.7). Additional features included trainable recognition, constraints based drawing and pin-up bulletin board. The designers could either share a drawing surface (tablet) or draw simultaneously on different tablets. They could also be located in different physical locations connected through a local area network. Likewise, SKETCHPAD+ was another prototype that was applied on a large design table. It included both pen-based digital input and a computer display where the users could draw with the pen (Piccolotto 1998). The sketches were afterwards translated into photorealistic renderings and the system could allow synchronous collaboration by having the prototype viewable on different displays.

Figure 3.7 The Electronic Cocktail Napkin—a computational environment for working with design diagrams. (Gross 1996) pp.53-69.

Further tangible interfaces for design purposes consisted of the HyperSketch prototype I and II (McCall, Vlahos et al. 2001) that simulated tracing paper by allowing users to trace previous designs and layer them on a LCD screen (Figure 3.8). Users could also identify relationships and links between different sketches in order to manage large collections of related sketches. Asynchronous and distant collaboration was supported through the Internet, "by enabling the creation, storage and retrieval of large collections of interrelated sketches from any Internet-enabled computer in the world" (McCall, Vlahos et al. 2001), p. 295. Additionally, the Luminous Table project combined 2D drawings, physical and digital models by utilising two cameras for space detection and video projection on a table surface (Ishii, Underkoffler et al. 2002). It achieved tangible interactivity by combining simpler technological parts and the design output was utilised for urban planning visualisations.

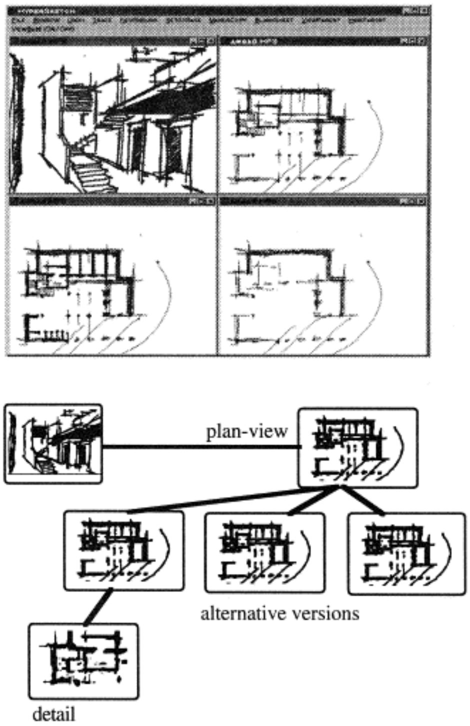


Figure 3.8 Conceptual design as HyperSketching. (McCall, Vlahos et al. 2001) pp.285-297.

Platforms supporting asynchronous collaboration and sketching include the Procedural Hierarchy of Issues Design Intelligence Augmentation System (PHIDIAS) hypermedia system (McCall, Bennett et al. 1990). The aim of the platform was to store and retrieve information about design decisions, whether it concerns words and documents or discussions on design projects, without attempting to manage workflow (Figure 3.9). Sketching processes have also been an extensive research focus, either aimed on rapidly conceptualising and editing simplistic 3D scenes (Zeleznik, Herndon et al. 2006), or on transferring free-hand sketches into three dimensional digital models through interpreting gestural and abstracted projections (Schweikardt, Gross 2000). Augmented Reality based applications for the conceptual stages within a sketch like environment comprise of tools like Hybrid Ideation Space (HIS) (Dorta, Pérez et al. 2008), that intents to augment digital pen and tablet displays with a real-time projection and normal perspective of the designed artefacts.

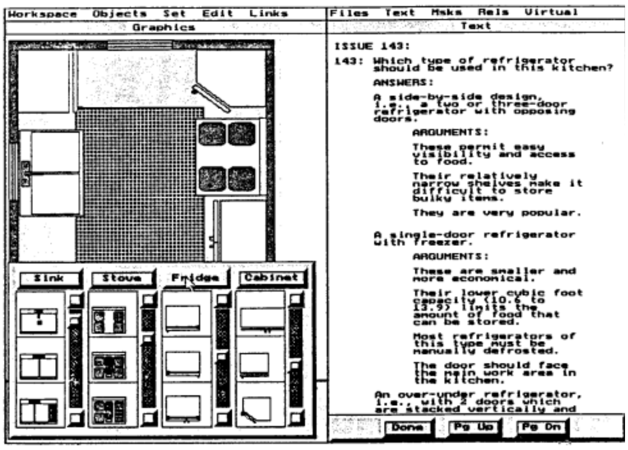


Figure 3.9 N. PHIDIAS: A PHI-based design environment integrating CAD graphics into dynamic hypertext. (McCall, Bennett et al. 1990).

3.3.3 Applications for the AEC Using M.S. PixelSense

Multi-touch display environments include proof-of-concept devices' combinations, like a multi-touch display with a Microsoft Kinect camera and two Gametrak devices to track movements above the surface for direct 3D modelling (Araujo, Jorge et al. 2012). Within the particular example, a menu provides the option to the users to move from linear to curvilinear extrusions. A division between dominant hand and non-dominant hand of the same user endows with different potential input, i.e. drawing with the dominant hand and option for points snapping or for 3D extrusion with the non-dominant one. The particular setup allows users to sketch directly on a touch screen and extrude on the third dimension by utilising a movement tracking option (Figure 3.10).

Figure 3.10 Kinect camera and Gametrak for direct 3D modelling (Araujo, Jorge et al. 2012). pp. 419-428.

Tangeo is a drawing interface applied on a touch-screen and utilising tangible drawing tools, like rulers and triangles (Zhen, Blagojevic et al. 2013). The aim of that interface is to allow the design of geometric shapes by employing finger design and traditional drawing tools (Figure 3.11). Users are capable of employing both physical artefacts that are tag-recognised by the PixelSense system. Ink beautification is another important aspect of translating the input into lines, by smoothing shapes and snapping corners.

Figure 3.11 Tangeo drawing interface (Zhen, Blagojevic et al. 2013) pp. 1509-1514.

Flo Tree (Chuan Chua, Qin et al. 2013) is a multi-user platform applied on a M.S. PixelSense, for exhibition and learning purposes in a museum (Figure 3.12). Museum visitors are able to spot a colourful set of lines moving on the screen that represent evolutionary biology. The interaction of the visitors with the PixelSense produces splits in the lines' continuity, conveying the challenges faced by populations, with the end result being the creation of new lines and therefore species. The interface includes a button for restarting the app, information bubbles explaining the exhibit and instructional images.

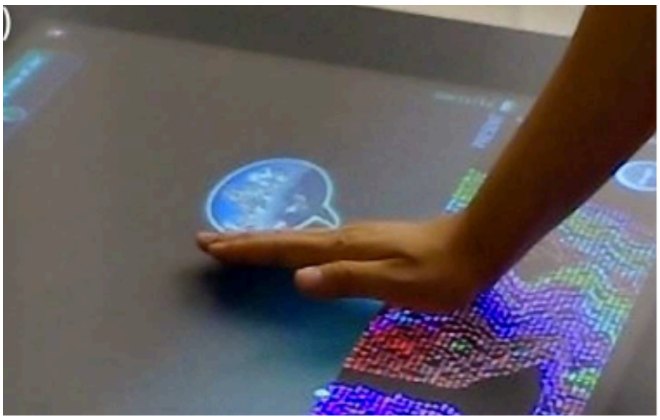


Figure 3.12 Flo Tree multiuser platform (Chuan Chua, Qin et al. 2013). pp. 299-302.

3.4 Development of the Computational Design Tool

3.4.1 Use of M.S. PixelSense during this Research

Drawing and sketching are the design mediums for conceptualising ideas especially within AEC industry and Tangible User Interfaces are the types of digital media that promote haptic experience. Therefore, **this research implements computer mediated environments (Tangible User Interfaces) to be facilitators for collaborative design, thus helping multidisciplinary professionals work together efficiently and effectively by supporting ideation processes.** The haptic experience is substantial for externalising and communicating visual ideas among design team members (Pallasmaa 2009; Schön 1991; Cross 1999). As a result and for purposes of the research, computer mediation hardware has been utilised for overcoming the technological barrier during conceptual collaborative design of complex problems that arise with human-computer interaction and smooth these interactions; this hardware is a Tangible User Interface (TUI), the M.S. PixelSense or M.S. Surface Table, developed by Samsung (Samsung SUR40 with Microsoft® PixelSense™). As it was described in Section 2.4.3, TUIs are the most suitable type of interfaces as they promote the haptic experience, which is so important for design ideation during conceptual design. Therefore, they can effectively tackle the technological barrier due to their tangible nature that reflects physical drawing while at the same time they can augment a digital enhanced environment and allow smoother integration with more complex and advanced design software.

PixelSense is 40” high definition screen of four-inch profile with a vision based multitouch system based on infrared sensing that allows for fifty-two concurrent interactions (Samsung SUR40 with Microsoft® PixelSense™), thus enabling experiments on computer mediated collaboration through visual and tactile user interfaces. The particular TUI enables simultaneous multiple participants’ interactions with the surface of the hardware through tactile and visual means, thus allowing for an immersive sketching environment by complementing human capabilities.

3.4.2 Reasons for Developing a Tailor-Made Design Application

During the progression of this research, it was required to develop a tailor-made design software for the M.S. PixelSense that would offer an augmented design medium focused on conceptual design and would smooth the transition between physical and digital environments. This design software was implemented during the design-brainstorming step of the CDSP within the studies.

The development of the design software for the PixelSense was led by the writer of the thesis and the computing side of it, the software creation, happened in collaboration with the School of Computing Science and Digital Media of RGU. A two months summer studentship, funded by the RGU IDEaS Institute, supported a last year undergraduate student of computer science to create the software under the close direction, refinement and supervision from the thesis writer. The application development brief is attached in **Appendix B**.

The particular application was utilised for two user studies on computer-mediated collaboration through visual and tactile user interfaces by multidisciplinary design teams of the AEC industry. Furthermore, the study examined the effectiveness of the system on designers' cognitive activities and design process in co-located multidisciplinary design collaboration experiment.

3.4.3 Development of a Computational Design Application

PixelSense was tested initially with off-the-shelf commercial design applications installed on it, the Windows Drawing application and Autodesk Sketchbook Designer. A number of problems were reported though, with the most important being that the Autodesk Sketchbook Designer is developed for a Microsoft Windows interface and is not adapted for PixelSense and multiple inputs. Additionally, even though the Drawing application enabled multiple inputs, the participants had difficulties utilising the design toolbars and technical difficulties prohibited the simultaneous use of multiple software, like searching for internet resources and bringing/importing information and pictures on the digital drawing surface. Problems were also discovered regarding the interface of the software, the commands, the poor quality of lines and the drawbacks with communicating effectively the different geometric shapes. Autodesk's AutoCAD was also tested on the particular hardware, and again similar problems were monitored, with the most prominent one being that the software was not developed with a focus on the particular TUI, rather it is developed for a Microsoft Windows personal computer; therefore, the multi-touch input could not be utilised. As a result, the development of a tailored application for the particular hardware that complied with certain design aspects was essential for the research purposes.

The development of a tangible conceptual design system/application was influenced by key overall principles from the literature review and from the results of the first testing, with the aim to achieve a natural design process. The interface of the developed app was designed to be non-intrusive to allow designers to fully engage on the design problems without any interruptions or problems coming from the interface. Minimising the modes and developing a small repository of operations aimed at a natural drawing process; the toolbar included options of actions, like importing pictures, drawing and picking a colour from a colour palette and taking snapshots. All the actions were available with a single touch on the screen allowing for a free-hand drawing surface, a paint tool that allows multiple users to draw at the same time with a selection of palette tools. Drawing and sketching were able to provide an easy and flexible externalisation of designers' vague ideas through a cyclic and dialectic process, since the ease of visualising and creating is a prerequisite for undisturbed creation. Working with layers on drawings was an additional developed tool for reflecting working with tracing paper, hence allowing easier restructure of drawings and their relationships, while keeping a track of the the design evolution. An image gallery was also integrated within the application, providing visual resources and inspiration. The users were able to choose the pictures they needed, import them on the canvas and take actions on them, like rotating, scaling or drawing over them. Taking snapshots to keep a visual record of the process was also an available feature, together with the choice to start a new canvas and delete lines and images when required. Eventually, the developed computer medium aimed at complementing the human capabilities by offering an augmented design medium focused on conceptual design.

Due to the nature of the action-based research, the evolution of the developed software is presented in each chapter related to the studies description. The first study described in Chapter 6 utilised the hardware with off the shelf software, to identify potential problems and investigate the available "off the shelf" design software applicable for TUIs. Due to difficulties presented in the studies it was required to develop an initial version of the computational design tool, which is presented in Chapter 7. It was tested during the second study, as explained in Chapter 7, and based on the feedback it was acknowledged that an update was required. Therefore, for the third study an updated version of the computational tool was utilised, and once again, its development is described in Chapter 8 together with feedback on the updated tool and its impact on the studies. Detailed pictures of the software during its development are eventually presented within Chapter 7, for the initial version of the design software, and within Chapter 8 for the updated version of the design software.

3.5 Summary

This chapter presented the two research deliverables according to the second objective of the thesis, the **Conceptual Design Stages Protocol (CDSP)** for conceptual collaborative design and the development of **a computational design tool for a TUI to act as a facilitator for conceptual collaborative design**.

Overall, the proposed protocol (CDSP) is based on rational design methods that encourage a systematic approach to design based on similar processes from engineering, design and management. CDSP forms a process with structured steps and at the same time allows space for creativity and brainstorming, it facilitates teamwork and allows for group decision-making. The subdivision of the task incorporates flexibility for different types of objectives, constraints and aims and at the same time is adapting to different procurement and project delivery methods. It is a process that aims at developing as a pre-BIM stage, for the purpose of smoothing out the conceptual stage and achieving a continuum with the BIM model and computer mediation. Importantly, conflicts are encompassed within the CDSP through the predicted iteration processes; argumentation among participants is supported and certain points during the process allow for reworking and reconsidering the evolved conceptual ideas.

This research further suggests a new role for design teams, the moderator of the Conceptual Design Stages Protocol, or else the “collaboration” manager. The purpose of this role is to further adapt the CDSP to the AEC industry. This role could be embraced from different types of professionals related to project management, design management or professionals that have a deep understanding of the multidisciplinary collaborative teams.

On the other hand, the computational design application for Tangible User Interfaces intends to integrate different sensory modalities for a richer and more coherent conceptual design through multiple tangible interactions. It is applicable to a specific type of hardware, the M.S. PixelSense, and its development was led by the researcher and conducted in collaboration with the School of Computing Science and Digital Media of RGU. Importantly, the developed design application had the purpose to create an augmented reality environment to further support collaborative design and extend relevant research in the field. The sensory modalities aimed to reflect the cyclic and dialectic process of drawing and sketching through multiple users’ operations by making use of the haptic experience.

4 Planned Methodology and Methods

Chapter 4 reviews and defines the planned methodology applied for the three case studies while moving from generic topics to more specific ones. This chapter initiates with a review of relevant research focused on monitoring collaborative processes. Afterwards, the chapter focuses on the thesis generic methodological approach, it presents the mixed methods applied during the thesis and the overall evolution of this research. The studies' research design follows, where all the different components of this research are described. Finally, the data analysis methods are presented, with a short review of the different available and appropriate approaches and the more specific description of the selected and applied methods during this research. The chapter's evolution is presented in Figure 4.1.

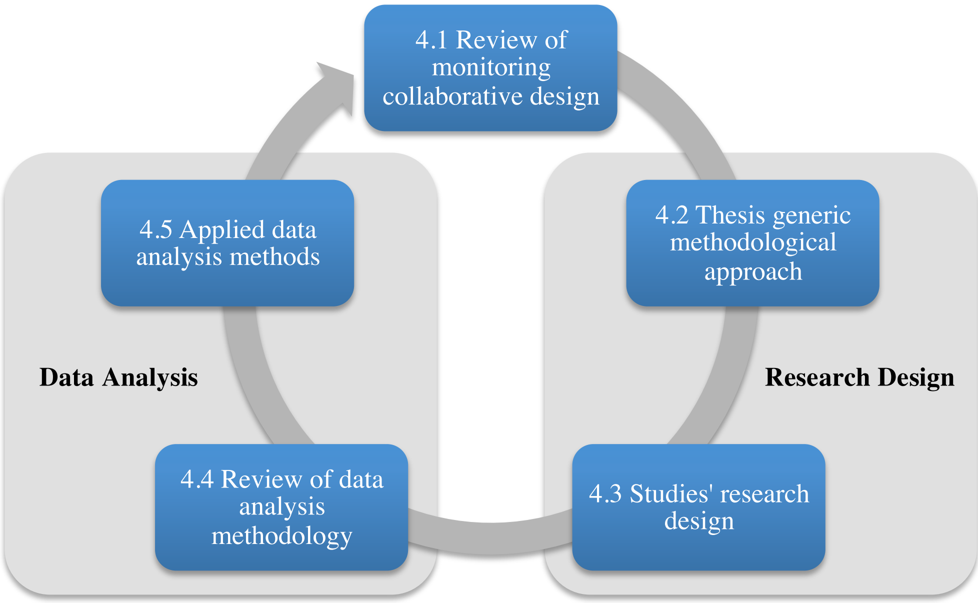


Figure 4.1 Chapter 4 sections

The next Chapter (Chapter 5) presents the results from eight semi-structured interviews and from two teams' shadowing; the data collected included notes and observations of 'shadowing' a design and a construction team meeting, while the purpose of this information was to provide additional feedback regarding practitioners' viewpoint on concept design stages. Chapter 6 until Chapter 8 describe the three studies that were undertaken and the comparison among the three of them is taking place in Chapter 9. Eventually, Chapter 10 closes the thesis with the answer to the initial research question and concludes with ideas for future development and research. A detailed explanation of the third objective and the relevant chapters is also presented in Table 4.1.

Table 4.1 The third objective of the thesis

Objective 3: *Facilitate and test both the current paradigm of conceptual design and the proposed CDSP, and undertake a critical comparison between the two.*

Objective 3:	**Relevant Chapters**
a. Review relevant methodologies for investigating design processes and determine the methods to be applied during the studies.	**Chapter 4**
b. Investigate the problems currently faced during concept stages within the AEC industry through interviews and meetings' shadowing to further support the research focus.	**Chapter 5**
c. Undertake a series of studies during which the current paradigm of concept stages and the proposed protocol and computational design application are tested.	**Chapters 6-8**
d. Compare and contract the results from the studies regarding the processes; the current paradigm and the CDSP.	**Chapters 6-8 and Chapter 9**
e. Compare and contrast the application of the current paradigm of design mediums and the tangible user interfaces for conceptual brainstorming.	**Chapters 6-8 and Chapter 9**

4.1 Review of Monitoring Collaborative Design

4.1.1 Observing Teams' Collaborative Processes: A Review

Previous research has been undertaken that aimed to monitor collaborative processes, including the observation of architectural design teams supported by computer tools (Ben Rajeb, Lecourtois et al. 2010). During this particular research two cases were described, the first one focused on collaborative design between architects in a lab and the second case on architects and engineers in real situation of design. The tools used for monitoring the experiments were digital desktops, videoconference and software called SketSha that allowed importing digital documents and sharing in real time annotations among collaborators. The platform was named Distributed Collaborative Digital Studio and it aimed to permit synchronous distant interactions (Lecourtois 2011). The aim of this research was to analyse computer mediated architectural design practices in order to identify the operations of conception. The methodology of these studies according to Ben Rajeb, Lecourtois et al. (2010) introduced the term "operations of conception", where the designer thinks and assigns measurements during the cognitive processes, the generation of ideas process. The "classes of operations of conception" define the concept of 'architecturological scales' which are the economic, functional and symbolic parameters of the different types of buildings that affect the ideas generation (Lecourtois 2012), and the drawings from the afforemntioned studies were considered through the filter of the applied architecturology and the relevant parameters. Furthermore, collaborative design was also analysed from a cognitive ergonomics viewpoint and the applied method was to count times and occurences of looks between the collaborators, sketching or writing actions, gestures and discussions. Overall, the particular research group attempted to monitor and analyse the interactions among the design team members according to designers' conceptual activities based on architectural parameters.

An additional example of studies, which aimed to apply Schön's theories into practice and to code teams' activities accordingly, involved dividing the design process into episodes (critical situations in other cases) where episodes were the parts of the protocol where one activity happens (Valkenburg, Dorst 1998). In the particular research student groups were chosen and the design process they followed was translated through Schön's theories with naming being the code name of each activity, frame being the design problem or sub-problem, moving being the action itself, like ideas generation and sorting information, and reflecting being the critical reflection of the previous actions. The purpose of this research was to improve team design in practice and to tackle the difficulties occurring in team design activities due to lack of synchronisation between different team members. The method followed in this example was to observe, analyse and describe team working on design problems of students' design teams in real-life situations and to construct a rich description according to Schön's theories. Videotaping teams' interactions was the method of monitoring applied during the research and the data were afterwards analysed in a way that described the team working on design problems. The design teams were comprised of different students' professions but the consistency is the same in all of the teams.

Participatory design methods as collective processes that eventually lead to cooperative design were also implemented for collaboration purposes in the example presented by Bratteteig and Wagner (2012), especially for engaging the public or the end-users. Participatory design and creativity were the research focus of these studies. Additionally, the methodology of the studies included implementation of both analogue and digital techniques and involvement of the end users within the decision processes of the early design stages. The digital tools of this research included a mixed reality (MR) Tangible User Interface with which the participants interacted and the whole process was recorded with a manually operated camera. What is more, the analogue tools consisted of hands-on visualisation techniques like drawing on simple resources (pen and paper). A qualitative analysis of the data followed with the researchers selecting significant video scenes according to their research questions and the conceptual framework.

Questionnaires are an additional method for observing the collaboration principles of multidisciplinary design teams, apart from camera-recorded studies. The research described by Peeters, van Tuijl et al. (2007) focused on critical behaviours and ways of investigating the observable characteristics of the critical behaviours that affect the overall design process. The research question in this case was how to establish favourable dynamics during designing that can result in successful completion of the project. The development of a Design Behaviour Questionnaire for Teams (DBQT) was employed for analysing the ways multidisciplinary groups work. Task analysis was implemented and the observed researchers and practitioners were asked to answer questions regarding the critical design behaviours, i.e. issues of communication, negotiation, reflection, and social processes.

4.1.2 Monitoring Collaborative Design and External Conditions

The term 'critical' is essential when describing situations during cooperative and collaborative design; the research of Badke-Schaub and Frankenberger (2002) focused on recognising these critical situations along with the methods to analyse the cooperative design processes. The techniques for identifying the critical situations included specific questions, individual search, and monitoring of passive transfer of information during informal talk. According to this research, social relationships' factors were more important than human error, operational or technical problems and having the designers identifying problematic situations and finding solutions for them was a key parameter for collaborative design. The researchers studied three laboratory teams collaborating for solving a complex problem and the cooperative product development led to a successful solution of the design problem. The conclusions of this research showcased that the teams focused not only on interacting on the content of the design process but also on structuring the group process. Additionally, the teams spent the majority of the studies trying to solve the design problem, a process that was mostly absorbed on a loop between analysis and evaluation of the proposed designs.

During the research conducted by Badke-Schaub and Frankenberger (2002), three factors determined the collaborative design comprised out of the designer, the group (complex systems of multiple professionals) and the external conditions (embedded context and culture, imagination). The research protocol for analysing the results was short time intervals of actions within a continuous design method; the utilised tools included observation, documentation and analysis of the design processes, with the technical observations on collaboration being accomplished by an engineer and the psychological aspects by a psychologist. Video recordings of the studies' duration were also employed in order to monitor the important design processes. Designers employed diaries as an additional method, where the problems and the solutions during the studies were being stated. Additionally, semi-structured interviews were employed for getting the designers' perspective. Finally, the external conditions were assessed by interviews, questionnaires and observations.

The critical situations during this research were categorised to ones related to the design problem context and to the social context (Badke-Schaub, Frankenberger 2002). In the case of the design problem context, the critical situations reflected issues that arose due to goals' analysis and relevant decisions, available information and solution research and analysis of the solutions and critical reflection. The solutions to these problems according to the research suggested a classification according to the actions' requirements, which were comprised of further clarifications of the projects and evaluation of the decision processes. In the case of the social context issues, the acknowledged social and psychological problems reported disturbance and conflicts among the teams' members. The solution proposed by the researchers in this case encompassed two aspects, avoiding the external disturbances and achieving a management of the conflicts with the intention of having a positive influence for the more advanced stages of work.

Collaborative design in relation to external conditions was researched by Dorta et.al (Dorta, Pérez et al. 2008) when utilising a Hybrid Ideation Space (HIS) with augment analogue tools for improving the ideas generation. The HIS (Figure 4.2) was a platform that allowed users to sketch and draw models in real time by using a digital tablet and a projection device, therefore, it promoted intuitiveness and ambiguity for generating ideas. This research acknowledged that ideation in collaborative design processes required cognitive artefacts for different visualisation methods and knowledge of the relevant technology. During this research, a set of freehand sketches and abstract physical models were utilised to generate ideas and the sketches were afterwards projected on a curved space that expanded all around the HIS platform. Groups, consisted of industrial and interior designers, were monitored while using the HIS for ideas conception and questionnaires were employed to assess the users' feedback regarding the artefact and the interactivity.

Figure 4.2: Immersive spherical graphical template – spherical sketch- captured image – spherical sketch over the image (Dorta, Pérez et al. 2008).

4.2 *Thesis General Methodological Approach*

The research question set in the beginning of the thesis aimed to investigate collaborative design through computer mediation and develop a set of relevant tools, a Conceptual Design Stages Protocol and a computational design tool. For the purpose of investigating and understanding complex interactions and thinking, like collaborative design, Dunbar (1995) proposed the use of in vitro and in vivo methods. In vitro methods is the type of studies "where individuals are brought into the laboratory and controlled experiments are conducted" (Dunbar 1995) pp. 462. On the other hand, in vivo methodology incorporates thinking and reasoning in a real-world context, for gaining insights in the "cognitive mechanisms underlying complex cognition and creativity" (Dunbar 1995), pp.462. The results from in vivo methodology can be encompassed and provide feedback to the in vitro research for controlled studies.

Similarly, this approach was utilised for providing answers to the thesis research question; the in vivo methodology was applied for an initial examination of the problems faced during concept stages within the AEC industry. A number of interviews and design teams' shadowing were recorded and qualitative input and information relevant to the collaborative processes was acquired. Based on that feedback and in parallel with it, three in vitro studies were developed, updated and informed. Even though the studies took place in a controlled environment, they simulated quite closely real-life situations. What is more, the first study aimed at identifying issues in collaborative processes and within the current paradigm of the AEC industry; as a result, the feedback was also partially considered as in vivo input.

4.2.1 Thesis Mixed Methods Research Approach

The thesis research objectives were focusing on both causality, or else why this research is important, and meaning, which translates to what is the topic of the research. As a result, research methods investigating both breadth and depth were necessary. The research gaps identification was achieved by making use of the inductive approach; the initial research hypothesis was developed through an extensive literature review as presented in Chapter 2. The initial research also assisted in limiting and specifying the research variables to be examined and focused the studies at particular causalities in relation to the research context. Following the identification of the research area, deductive methods were applied for developing the studies, testing the research deliverables (the CDSP and the computational design tool), analysing the results and producing the descriptive statistics.

In general, qualitative research can be language based, including understanding and interpreting language, gestures and texts. Additional aspects of qualitative methods are narrative, descriptions, hypothesis testing and theory development out of data collected during studies. Qualitative research is moving from generic to context specific through a number of iterations, thus evolving from generic approaches to the research topic and the relevant theories towards the specific and refined results (Miles, Huberman et al. 2013). In the particular case, the qualitative input that informed the thesis was the literature review together with a series of semi-structured interviews and two teams' shadowing processes.

On the other hand, quantitative approach involves conducting measurements in collected data. That type of data is derived from studies, which are constructed according to previous knowledge, data requirements and research questions, thus moving from in vivo to in vitro methodology (Dunbar 1995). An examination of the objectives of the project together with previous research findings can assist at selecting what needs to be measured and the right scale of measurement (Fellows, Liu 2008). Quantitative methods require a considerable amount of pre-determined decisions regarding the type of data to be collected and, therefore, a qualitative approach is required prior to quantitative one.

Quantitative methods utilised during the thesis for the purpose of gathering data included carrying out three studies and having questionnaires at the end of each study. The studies were analysed according to two different analyses, Protocol Analysis and Activities Mapping. The data collected from these analyses were further investigated according to statistical approaches and based on the nature of research, as Fellows and Liu (2008) and Balnaves and Caputi (2001) research suggested. A summary of the generic quantitative and qualitative methods used during the thesis is compared in Table 4.2, as adapted from Mack, Woodsong et al. (2005).

The mixed-methods research approach, where both quantitative and qualitative approaches were used for data collection as depicted in Figure 4.3, allowed the flexibility to adapt according to the research objectives. The thesis followed an action-research approach for testing the conceptual design processes during the three studies since input from every study was feeding into the following one and therefore the developed Conceptual Design Stages Protocol and the computational design tool were being updated after every study was concluded.

Table 4.2 Comparison of quantitative and qualitative research according to Mack, Woodsong et al. (2005) and adapted for the research according to different chapters

	Quantitative (Chapter 6-9)	**Qualitative (Chapter 5)**
General Framework	• Confirming hypotheses about conceptual and multidisciplinary design • Utilising structured methods like questionnaires and structured observations	• Exploring conceptual and multidisciplinary design through a series of studies • Utilising semi-structured interviews and participants observations (teams' shadowing)
Objectives	• Quantifying variations and statistical analysis • Describing characteristics of a population	• Describing variations • Describing characteristics of relationships, group norms and individual experiences
Data Format	Numerical	Textual
Study Design Flexibility	• Study design remains the same from start to end • Study design is subject to statistical assumptions and conditions	• Study design is flexible and it can adapt according to the type of professionals • Study design is iterative and data collection methods can adjust according to input

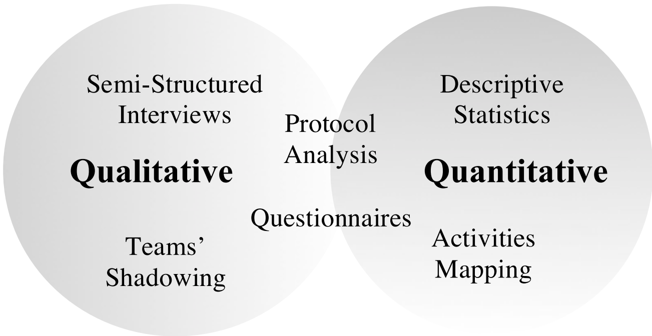


Figure 4.3 Thesis mixed methods approach for data collection

Grounded theory was applied for reaching the final conclusions of the research as derived out of the acquired data and out of the context of the research. Grounded theory is a methodology for deriving theories out of structured data set regardless of the existence of an initial research question (Glaser, Strauss 1967; Hunter, Kelly 2008). The methods for extracting these theories can be both inductive (Glaser, Strauss 1967) and deductive (Strauss, Corbin 1998). Eventually, this thesis followed a process where theories emerged from a combination of literature, observations, common sense and experience (Cutcliffe 2000) for detecting whether the thesis research question was answered.

4.2.2 Evolution of the Thesis 3rd Objective

The research followed a highly iterative process due to its action-research nature; the answer to the research question was to provide a design process that could enhance multidisciplinary collaborative design assisted through computer mediation during concept stages of architectural design. Consequently, a reflective process was followed during the research progression, where the acquired input after the completion of each study or set of interviews was feeding into the research development, as illustrated in Figure 4.4.

Three different studies were employed for understanding the design process adopted by design teams and for testing the adoption of the Conceptual Design Stages Protocol. The first study, that took place in May 2013, was an exploratory one and it aimed at identifying the existing conceptual design processes. During this study the professionals followed a conceptual design process based on their previous knowledge of these processes and according to the current paradigm in AEC industry for conceptual design stages.

During the first study the focus was on the process a team follows by default, that being the current paradigm of conceptual design, while the dynamic evolution of the conceptual design was being monitored during the development of the experiment. This study also focused on the digital platforms in respect to principles for effective collaboration among multidisciplinary design teams and the processes the participants followed to integrate these means to the conceptual design process. The team utilised the M.S. PixelSense with "off the shelf" commercially available design software. The qualitative and quantitative data were derived from the recorded interactions and actions descriptions of the whole duration of the study, from questionnaires and from a final discussion. What is more, any type of documents utilised by the participants during this process were also considered part of the monitoring process. The individuals and the groups' prerequisites were comprised of information relevant to the expertise of the individual participants and the different interactions and group dynamics within the groups.

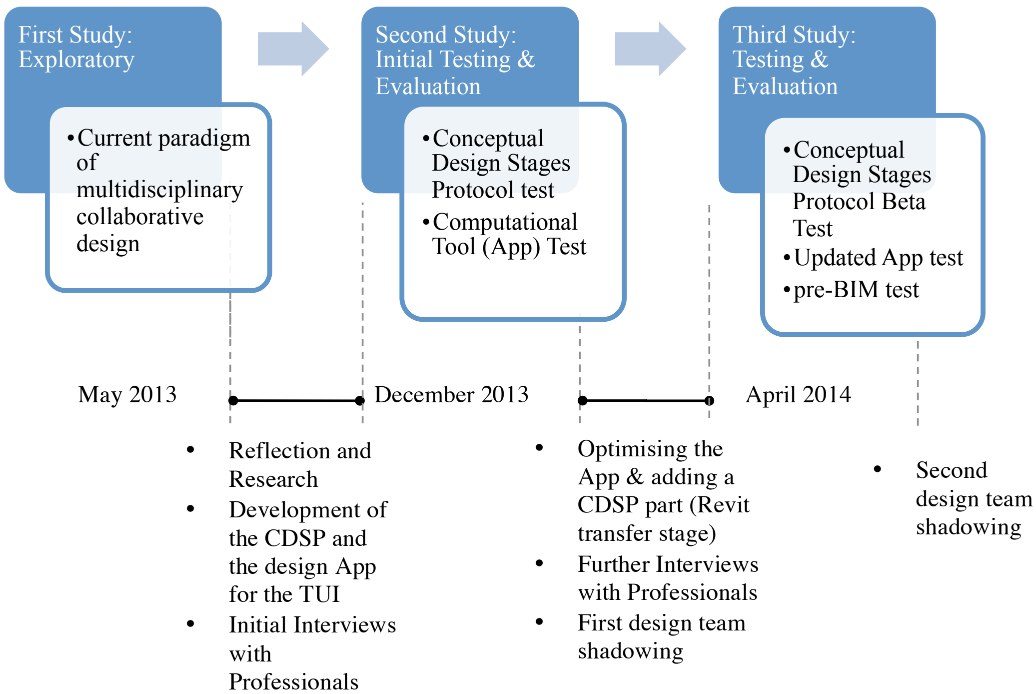


Figure 4.4 Studies' evolution

Following the results from the first study, further reflection and clarifications had to take place. The outcomes regarding the communication, brainstorming, collaboration and the overall process the team followed provided the learning steps to update, inform and improve the studies. The Conceptual Design Stages Protocol was created and a new computational design application was developed for the M.S. PixelSense. Furthermore, both the facilitation process and the design brief were changed and improved in order to be applied for the second and third study. The first three interviews took place during the time between the first and second study for further identifying the problems with collaborative design during concept stages. Crafting the research according to the literature and the feedback from the first study was essential for the research development and for answering the research question. The overall evolution of the research is presented in Figure 4.4.

The second study took place in December of 2013, and it applied the predefined Conceptual Design Stages Protocol (CDSP) during the conceptual stage, making use of a managed facilitation process throughout the design project. After the conclusion and reflection on the second study the outcomes suggested further enhancements of the Conceptual Design Stages Protocol by integrating and testing a pre-BIM stage within the third study. Furthermore, computer bugs were experienced when using the developed computational tool that had to be fixed, as a result the application needed to be updated. The rest of the interviews and the first design team shadowing process took place between the second and third study as well. The third and final study was in April of 2014 and it was focused on testing and evaluating both the CDSP and the updated design application applicable to the M.S. PixelSense. After the completion of that study a second team shadowing was arranged for further input from the industry.

4.2.3 The Three Studies Generic Methodology

The methodology for researching collaborative and conceptual design processes and ICT during feasibility and concept stages included setting up the Conceptual Design Stages Protocol and testing these steps by implementing digital media technologies and interactive and smart surfaces. The whole process was tested in three different studies and these included multidisciplinary groups of professionals/designers from the AEC/FM industry, i.e. architects, civil engineers, mechanical engineers, project managers and surveyors. All three studies were video recorded and were set up as Study Groups. The digital tools that were utilised included the Microsoft Surface Table, PixelSense with different types of design software. The capabilities and the affordances of various digital media were also part of the research and testing. The studies took the form of brainstorming sessions; a design brief was handed in the beginning of all studies that was about a conceptual design solution for a small educational and research building. The development of a design solution for the given brief allowed monitoring of the ideation processes during concept stages of design. The researcher and writer of this thesis was the moderator of the studies who introduced the task to the participants and ensured that the teams were following the pre-defined Conceptual Design Stages Protocol (CDSP) during the second and third studies. Additionally, information gathered through these studies provided the quantitative and the qualitative data to feed into research and certain conclusions were drawn from them. The three studies progression is presented in Figure 4.4.

4.3 Studies' Research Design

4.3.1 Studies' Structure

All three studies had a particular structure, with an introductory presentation in the beginning, followed by an ice-breaker, which was an important component for building up the collaborative team quickly and effectively (Curedale 2012). The introductory discussion aimed at assisting the participants to immerse into the topic and the design task they were asked to accomplish. Afterwards, the task explanation followed, which was the conceptual design of a small scale office space that followed specific requirements i.e. size in square meters, types of spaces included in the building and a certain site. The first stage of the actual design process initiated, again within certain time duration of an hour and a half. Following a short break, the participants were introduced to the TUIs that they were asked to use for the second stage of the study; that stage was lasting forty-five minutes, during which they were asked to further develop their ideas by using the computational mediums. Certain time slots decided the duration of the process and the participants were informed both beforehand and during the process about their available time left. The last part of the studies included the presentation of the conceptual design and a short discussion with the participants on the process. Figures 4.5-4.7 illustrate the structure of all three studies with the small differences among them being underlined and further details being provided in the information box of each study.

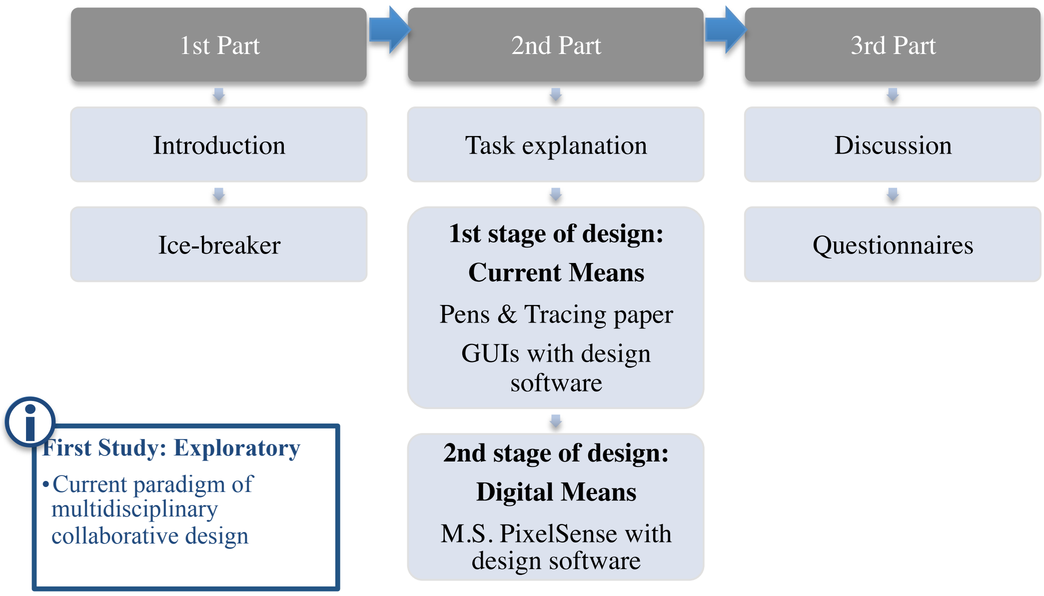


Figure 4.5 First study structure

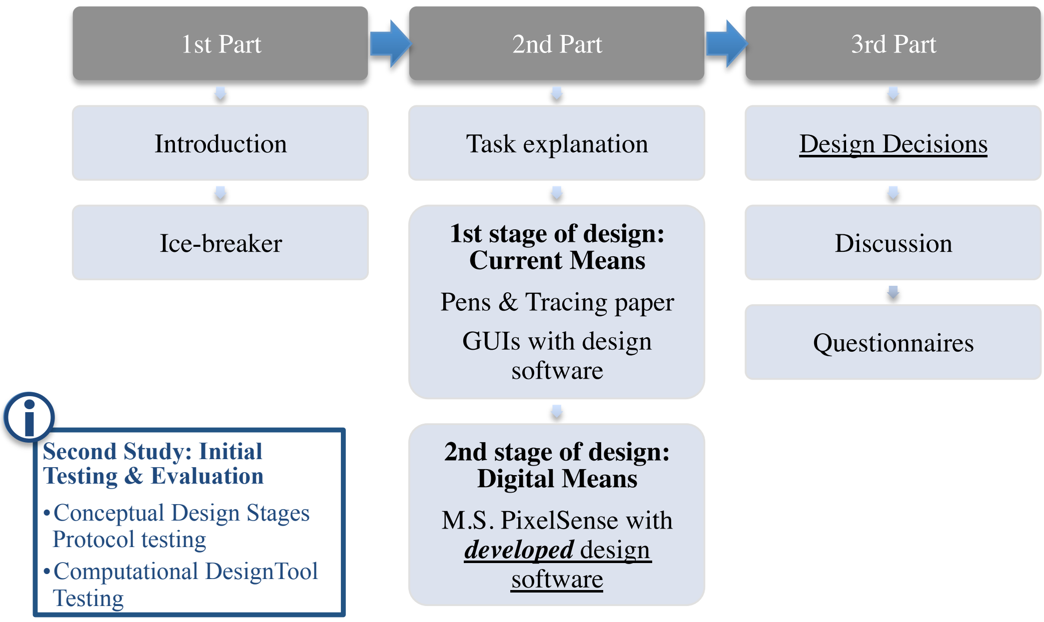


Figure 4.6 Second study structure

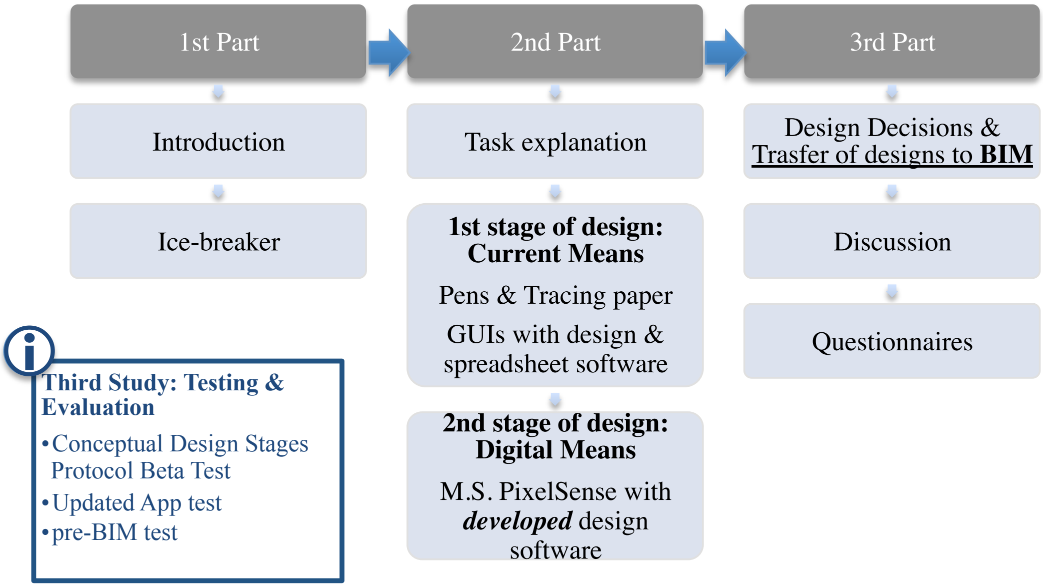


Figure 4.7 Third study structure

The division of the second part in two stages was essential for additionally testing the computer mediation aspects of the research and it was the key factor that decided the choice of the available means utilised for conceptual design; during the first stage, any type of drawing tools designers tend to use during sketching were available to the participants together with a laptop with internet connection, while during the second stage of the study, the Microsoft Surface PixelSense was the proposed medium for conceptual design. The two parts lasted for two and a half hours with half an hour break, and each different aspect of the experiment had particular time slots. A short break distinguished the transition between the analogue and the digital design mediums stages, followed by a brief introduction on the Microsoft Surface PixelSense and a few warm up games on it. Afterwards, the design process continued by utilising the TUI with a totally different setting compared to the previous one; all the participants were around the Table and it was an actual hands-on experience for all of them. Finally, when the design process was completed, the moderator initiated a discussion, which was followed by questionnaires to be answered by the participants.

4.3.2 Studies Components

The aspects and methods that needed to be identified and addressed in all the studies included the design brief for the experiments, the introductory information and process, people who would be involved, provided and available digital means/ the framework and potential methods for addressing the design problem. Additionally, more technical issues that had to be tackled included the monitoring process, the identification of critical situations, the ideal length of the task, the anticipated outcomes and any unpredictable technical problems. The totality of all these aspects is presented in Table 4.3.

Table 4.3 Generic studies' components

Design Brief	▪ Creation of a conceptual design for a small scale project
Participants & Study Groups	▪ Multidisciplinary groups of students/ professionals
Available Physical and Digital Media	▪ Physical means (pens and tracing paper, maps' printouts, drafting mediums) ▪ Digital means (GUIs and TUIs)
Method	▪ The current paradigm of conceptual design regarding design mediums ▪ By utilising the framework / digital means
Monitoring	▪ Digital media (cameras), interviews and questionnaires
Aspects to be examined	▪ Design process ▪ Design prerequisites ▪ Task/ design brief ▪ External conditions / technology
Critical Situations	▪ Evolution of the creative process ▪ 'Stuck' moments
Anticipated outcomes	▪ Identify technical problems during the studies ▪ Identify and standardise the design steps and protocol
Study Group Facilities	▪ Meeting rooms within RGU premises

4.3.2.1 Design Brief

The design brief of the experiments required participants to create a conceptual model for a building, with the budget, regulations and anticipated deliverables provided beforehand. The required task was the conceptual design of a small-scale office space that developed through a brainstorming session. The steps the participants applied for ideas generation during the studies were closely monitored for all three studies, irrespectively of the different aims of each study. An introductory discussion assisted the participants to immerse themselves into the topic and the design task.

4.3.2.2 Participants and Study Groups

The studies took the form of Study Groups and included interactions of the group members among them and with the moderator of the group for identifying and investigating areas of interest to the moderator (Morgan 1997). Study Groups (S.G.), like Focus Groups (F.G.), include a threefold type of participants, the researcher/moderator, who organises the focus group in the first place and who is actually looking for particular type of information from the S.G., the S.G. itself, comprised out of different people attending the group, who create the conversations on the chosen topics, and the analysis and research of the final results, which is either conducted by the moderator or other researchers. The research aimed at providing answers to research questions that have been set at the stage of organising a focus group. Since the S.G. consists of multiple people there are less details about the unique people and more information in active comparisons of opinions and shared experiences, which is a suitable method for answering research topics relevant to collaborative design. The studies' participants in all three cases were multidisciplinary groups of AEC professionals or, in the case of the last study, graduate students. Further details about recruiting participants of the studies and interviews are described in Section 4.3.7.

4.3.2.3 Available Physical/ Digital Media and Method

The resources and media available to the designers during the studies were those widely used in professional practice. These included physical media, like tracing paper, markers and the current paradigm of hardware (laptops) with commercial design applications. In addition to that, a particular TUI was used, the Microsoft Surface Table with Microsoft® PixelSense™ . The studies were divided in two main parts, with the first one including the participants developing the conceptual design the way they used to do (the current paradigm of media) and the second one, to develop it by utilising the digital tools and platforms. Furthermore, the typical meeting room setting for facilitating the studies including both physical and digital design mediums and media is presented in Figure 4.8.

As Frascari stated (2011), architectural drawings are a suitable tool for constructing drawings and drawing constructed thoughts; as a result, the current paradigm of tools and design and drafting instruments were suitable to provide to the studies' participants the haptic experience of design, drawing and of ideas evolution. The physical drawing instruments aim at contributing to the affordances of the environment and they invite for certain actions, thus promoting a relationship between designers' body, mind and instruments. This relationship supports the translation of design information into sketches, drawings, diagrams and 2D or 3D representations that convey architectural design solutions, and further details on sketching and cognition can be found in Chapter 2. The physical means available to the participants were drafting and measuring tools including triangles and scaled rulers, pencils, colour pencils and markers, tracing paper and drawing paper, copies and printouts of the surveying data of the area and pictures of the area (Figure 4.9). Additionally, physical brainstorming tools were also provided and these included post-its for organising and categorising their ideas, a flip-chart board and a magnetic board with hexagonal pieces in two colours, a suitable tool for making connections between spaces and ideas (Figure 4.10).

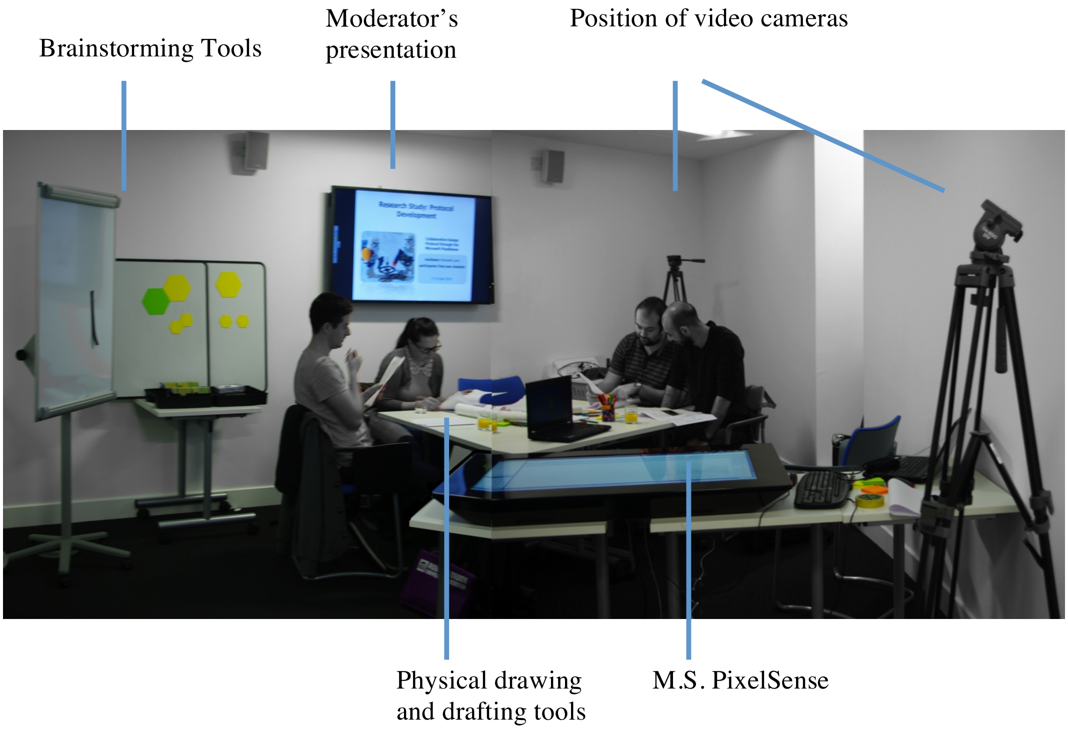


Figure 4.8 Typical room set-up for the whole duration of the studies

Figure 4.9 The provided physical design mediums at the beginning of each study

Figure 4.10 Available brainstorming tools, magnetic board in use

4.3.2.4 Studies' Monitoring and Critical Situations

The whole process of the three studies was video recorded; two video cameras on tripods were placed on the two ends of the room where each study was taking place as presented in Figure 4.8. The purpose of these cameras was to make sure that all the different and concurring processes were monitored, from the initial presentation, the brainstorming both with physical and digital means up to the use of any additionally provided means. What is more, the moderator of the studies kept a track record of pictures and notes for each study. The monitoring process also included an open discussion and questionnaires at the end of the studies for reflection on the experiences the participants had together with any comments on the hardware. The rationale behind this monitoring was to identify through content analysis and descriptive statistics the critical situations during the ideas generation, to investigate the role of digital media and to reveal possible problems both with the S.G. and with the collaboration processes. Furthermore, the monitoring assisted at pinpointing the design process, the steps that the teams followed to reach the end-result, including the ideas generation moments and the instants where the progress was stagnating and there was miscommunication of ideas.

4.3.2.5 Aspects to Be Examined

The positive critical situations include the creative process and the ideas generation, the mechanisms that assist it and the role of digital media, while the negative situations involve the moments where there is a lack of creativity and ideas. What is more, the critical situations from the first study together with the relevant literature review provided the important feedback for the development of study two and three. The last two studies were focused on developing the answer to the initial research aims and objectives. The whole experimental process for every study lasted for three and a half hours with one hour approximately for each part of the studies. Each different aspect of the studies had a certain time slot and they were the same for all studies. Additional affecting factors that were considered comprised of constraints, like time and attention. Clarity of the tasks and directions were also important aspects together with personality characteristics of the participants.

4.3.2.6 Anticipated Outcomes

The anticipated outcomes included the identification and optimisation of the protocol/ design process that is followed throughout the conceptual design, when employing digital tools. The anticipated technical problems included issues with the machinery and software such as the capabilities of the Microsoft Surface PixelSense and setting up cameras and digital equipment before each study.

4.3.2.7 Study Groups Facilities

The studies were hosted on RGU University premises and a meeting room was a suitable place that could facilitate both the needs of the research to accommodate the provided media and also ensure the comfort of the participants. These rooms were located in the former campus of School of Computing Science and Digital Media, in St Andrews Street, and in the new RGU Campus in Riverside East. The rooms had a pleasant environment and included not only the suitable electronic facilities and furniture but also they had windows and good quality of air and light. However, due to technical restrictions with The M.S. PixelSense, it was essential to restrict the sunlight during the second stages of the studies. The TUI was sensitive to light and bright daylight was having an impact on the users input, thus causing problems to the use of the TUI.

4.3.3 Digital Media and TUIs

A key difference between the three studies is the computer-mediated design aspect. During the first study, the participants utilised the M.S. Pixelsense with "off- the shelf" commercially available design software (drawing application, Autodesk Sketchbook Designer, AutoCAD). Following the conclusion of the first study, the writer of the thesis observed and recorded the problems users were facing, which led to the development of tailor-made design software, a conceptual design application developed specifically for the project and for the M.S. Pixelsense, as described in Chapter 3. The developed software was used during the second study and it included a small repository of operations, aiming at an intuitive drawing process. The developed software toolbar integrated options of actions like importing pictures, drawing and picking a colour from a colour palette, taking snapshots, drawing on images, working on layers and importing pictures. For the third study, the application was updated and it was again utilised for the conceptual design of the team.

Table 4.4 Design mediums and digital media during a design team meeting

Current paradigm of design mediums	Digital media
Hand-drawn sketches	Digital sketches and drawings
Site information (pictures)	Spread sheets with info and calculations
Site information (maps with contour lines)	Site drawings
Drafting tools	Internet resources
	Input from different types of software

The participants had also the opportunity to take advantage of additional digital media; these included a laptop with Internet access and with installed drawing and statistical software while a desktop with a connected projector was used for the moderator’s presentation. The overall physical design media and digital media are summarised in Table 4.4.

4.3.4 Brainstorming Methods

According to Curedale (2012) a brainstorming group should include a director/moderator and the number or the people should not be less than five and more than fifteen, since less people consist an opinion and more people face difficulties in cooperation. For the research purposes, that group should also include as many different AEC professional viewpoints as possible. It is also essential not to apply hierarchy within the group since the moderator’s role is to guide the group during the brainstorming process without affecting or criticising the opinions.

The participants made use of a number of design and brainstorming methods for stimulating design ideation while trying to increase the flow of ideas. Creative methods were essential for providing solutions to design problems since, according to Cross (2008), conceptual design process requires the generation of a large number of ideas where only a few of them are typically identified as suitable for further elaboration. The participants made use of a number of brainstorming processes, even if they were not aware they followed these methods. Parallel or lateral thinking process was one of them, which is a creative method that allows for mind patterns to be reconstructed thus leading to creative insights (Butler-Bowdon 2006); a process highly supported from the multidisciplinary teamwork. Furthermore, the different personalities among the participants allowed for an adaptation of the ‘The six thinking hats’ (De Bono 1990), where different mind-sets are asked to collaborate. The hats process initiates after the creation of a shared vision, with different personalities involved in the solution finding. In the ‘six thinking hats’ methodology, the six personalities included a focus on information, on emotions, on logic, on positivism, on creativity and on team’s management. Similarly, due to the different participating personalities, each professional did not only contribute according to their profession but also according to their character. An additional acknowledged brainstorming process the teams followed included the method 365, where the proposed solutions were examined by all participants until a common conclusion was achieved (Curedale 2012). This method bares similarities with the Delphi method where the experts of a field are asked for written opinions within a series of tasks, with the first one being the spontaneous solutions/suggestions, followed by the second round with over viewing of the previous results and suggesting further development.

4.3.5 Questionnaires

Questions' development was an additional important aspect of the Study Groups (S.G.) for the progression and evaluation of all three studies. These questions were both oral and written; hence, they were part of the studies' presentation and process and also were included in distributed printed questionnaires. The core principles of developing questions for a S.G. included keeping a conversational tone during the questions, making the questions simple, clear and easy to understand, avoid asking why but replace it with questions like 'what prompted you?' or 'what features do you like?', providing adequate time for developing quality questions and experimenting until the questions actually work, according to directions for questions from Krueger and Casey (2009). The strategies for developing questionnaires were comprised of the topic guide and the questioning route, with the first one being the list of issues to be pursued during the S.G. as keywords and not as developed questions, while the second was having certain and specific questions built beforehand.

The studies questions' development initiated by clarifying the problem and identifying the key issues and questions that had to be addressed for obtaining the necessary feedback from the participants. The first study tested the initially developed questions and these were adapted for the following two studies. During the S.G. different types of questions were required for the different stages, including opening, introductory, transition, key and ending questions (Krueger 1997). The constructed questions moved from the general ones to the specific ones. The opening questions were the ones at the beginning of a S.G. that motivated the participants to talk and establish a sense of community among the participants (ice-breaking questions). The introductory questions were the ones following up that initiated the topic of the discussion and provided an opportunity to participants to reflect on their personal experiences and relate to the topic. The particular type of question provided valuable insight about the participants' pre-constructed theories about the researched topic and how do they affect the S.G. These questions provided feedback and fostered further follow-up questions and discussions among the participants. Furthermore, the moderator asked the participants a number of transition and key questions for the purpose of assisting them envision the wider spectrum of the study and allow the study moderator to move forward the studies. The end questions were the ones closing each of the three studies, thus, enabling participants to reflect on their experience and provided useful comments and discussions on the process. The types of end-questions included the all-things-considered ones, the summary question and the final one. The type of questions that were utilised for the questionnaires had a similar structure; opening questions were part of the introductory part regarding their previous knowledge followed by more detailed ones on the processes, the end result and their overall feedback.

4.3.6 Self-Rating Tools

The collected data from studies two and three included an additional tool where the participants self-evaluated individually the design solution and rated their conceptual design. The participants' opinions were measured numerically by implementing an answering scale, ranging from one to five. The rating tool is a Design Quality Indicator (DQI) developed by Construction Industry Council for measuring and evaluating design quality among the project's stakeholders (Gann, Salter et al. 2003; Prasad 2004a; Commission for Architecture and the Built Environment 2011). The rating tool development was based on Vitruvius design qualities, "Utilitas, Firmitas and Venustas" (Vitruvius, Morgan 1960) that describe design qualities based on 'commodity, firmness and delight'. Design quality is a totality and not the sum of parts according to Prasad (2004b) and the three quality fields in the rating tool included functionality (use, access and space), built quality (performance, engineering systems and construction) and impact (form and materials, internal environment, urban and social integration, character and innovation), in a synergistically approach. An example of such a tool is presented in Figure 4.11.

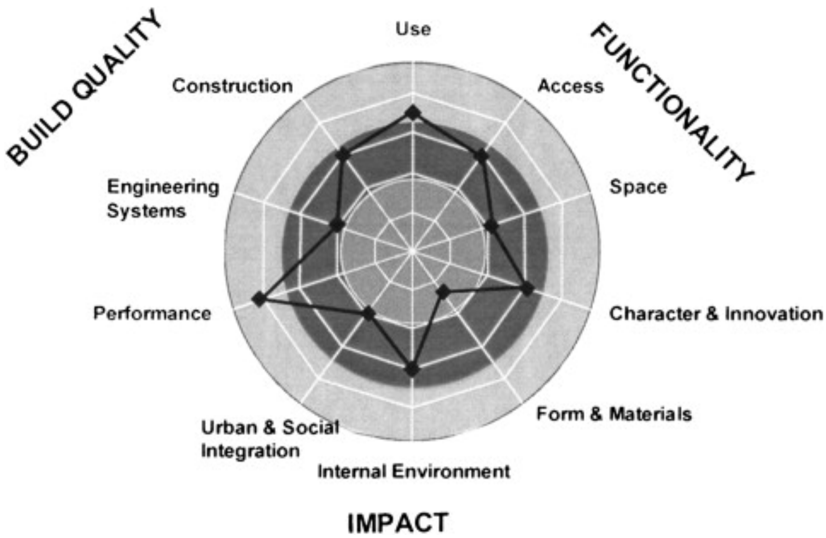


Figure 4.11 Example of a project's quality estimation by using DQI (Gann, Salter et al. 2003)

4.3.7 Recruiting Participants

The S.G. participants were multidisciplinary groups of professionals/designers from the AEC/FM industry. The participants were PhD researchers and staff from Scott Sutherland School of Architecture and the Built Environment, with former experience in the AEC industry. Studies Group participants were chosen with particular attention and they were comprised of people who already know each other from beforehand; the reason being that the exploratory study actually reflects the practice in construction design teams, with the team members knowing each other or having worked with each other from beforehand.

Specifically, the participants of the first study included two architects, a surveyor, a project manager and an architect/structural engineer. They all had similar experience of a few years post qualification with the exception of one senior member and the all knew each other from beforehand. During the second study, the participants comprised of two architects, a quantity surveyor, a building surveyor, a mechanical engineer and an architect/ structural engineer; all of them had some experience post qualification with the exception of two senior professionals this time. Eventually, the last study was comprised of final year students of Scott Sutherland School of Architecture and the Built Environment, again maintaining the multidisciplinary aspect of the research among young professionals, including two architects, an architectural technologist, a quantity surveyor and a building surveyor. Concerning the interviews and teams' shadowing, senior professionals of the AEC industry were employed and interviewed or monitored. The total number of participants is represented in greater detail in Table 4.5.

Table 4.5 Data collection, number of participants and relevant chapters

Studies	Data Collection	Number of Participants	Thesis Chapter
First Study: Exploratory	• Protocol Analysis • Questionnaires • Discussion	5	Ch. 6
Second Study: Initial Testing and Evaluation		6	Ch. 7
Third Study: Testing and Evaluation		5	Ch. 8
Shadowing	Monitoring a Design and a Construction team	2 teams, 8 participants in each team	Ch. 5
Interviews	Semi Structured Interviews	8	Ch. 5

4.4 Data Analysis: A Review

The studies analysis involved re-examining a number of audio and video recordings of each study. Protocol analysis and activities mapping were the preferred methods for analysing studies outcomes. The particular methods have been used extensively for analysing studies focused on design problem solving, on design cognition, like Gero and McNeill (1998), Suwa, Purcell et al. (1998) and Salman, Laing et al. (2006), on designers' collaboration and interactions with computer mediums, like Gu, Kim et al. (2011) and Kim and Maher (2008). Further research on mapping the design activities includes conceptual activity of interdisciplinary teams, according to Austin, Steele et al. (2001) and Macmillan, Steele et al. (2002), and comparison of engineering and construction design stages, like an additional example from Macmillan, Steele et al. (1999).

Protocol analysis was utilised within the thesis for analysing the video recordings of the three studies showing users' interactions among them and with the design media, both physical and digital. The coding scheme is based on identifying the perceptual, cognitive and collaboration activities during the study. Subsequently, the coding categories answer to questions on the physical act of drawing, the cognitive mechanisms underlying the processes and the collaboration among the participants.

4.4.1 A Review of Macroscopic Analysis of Design Processes

Three distinctive approaches for a macroscopic analysis of the studies data have been identified. To begin with, the macroscopic analyses of design processes of architects as presented by Gero and McNeill (1998) aimed at defining designers' cognitive actions in a systematic manner during the design stages and at providing further insight in the designers' sketching processes. The protocol analysis stages included the segmentation of the verbal protocols according to subjects' intentions and the contents of their thoughts or actions. Afterwards, these segments were categorised according to different types of actions, which depended on the perspective of the analysis. Gero and McNeill (1998) analysed them according to the cognitive processes and therefore the categories corresponded to physical, perceptual, functional and conceptual actions. A description was agreed for each of the actions and the segments were coded accordingly. As a result, different kinds of relations among the design actions could be identified and correlations between different actions were also feasible, as presented in Figures 4.12 - 4.14.

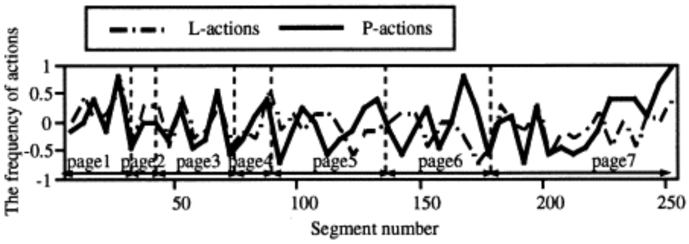


Figure 4.12 Correlations between perceptual actions (P-Actions) and looking (L-Actions), (Suwa, Purcell et al. 1998), pp. 477

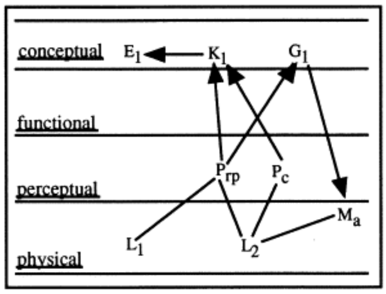


Figure 4.13 Relations among design actions for a segment (Suwa, Purcell et al. 1998), pp. 471

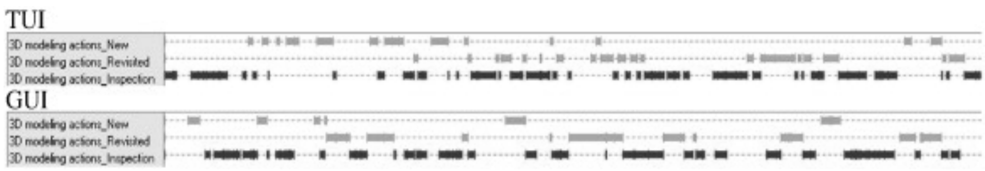


Figure 4.14 3D modelling actions according to time spent on each level, (Gu, Kim et al. 2011), pp. 276

Likewise, protocol analysis steps as described by Gero and McNeill have been adapted by Gu, Kim et al. (2011) for a research focusing on the impact of technology and different computer mediums on designers' cognition for architectural design. The particular research analysed designers' interactions with different types of GUIs and TUIs during conceptual design and monitored the effects of technology on collaboration, communication and interactions among the designers. Afterwards, the segments of designers' activities were categorised according to four levels, the collaboration level, which includes cognitive synchronisation, perceptual level for perceptual activities, the action level for modelling actions and the process level for setting up goals. The authors analysed the designers' behaviour for specific computational mediums and compared the categories of codes according to how much time designers spent on each level. The aim of that research was to showcase how collaborative design technologies can support remote and co-located collaboration and encourage and engage designers during these processes (Figure 4.14).

Suwa, Purcell et al. (1998) devised a coding scheme for analysing the design task of an art museum in a given site. The task lasted for forty-five minutes and the participants produced a number of sketches and drawings, with the whole duration being videotaped. The researchers afterwards analysed the recordings and divided the verbal protocols in smaller segments. Four different main categories were utilised, including physical, perceptual, functional and conceptual actions. The four categories were classified according to the way human cognition is supposed to process incoming information, through sensory, perceptual and semantic levels. Further details of the particular coding scheme are presented in Table 4.6.

Table 4.6 Action categories (Suwa, Purcell et al. 1998), pp.460

Category	Names	Description	Examples
	D-action	Make depictions	Lines, circles, arrows, words
Physical	L-action	Look at previous depictions	–
	M-action	Other physical actions	Move a pen, move elements, gesture
		Attend to visual features of elements	Shapes, sizes, textures
Perceptual	P-action	Attend to spatial relations among elements	Proximity, alignment, intersection
		Organise or compare elements	Grouping, similarity, contrast
Functional	F-action	Explore the issues of interactions between artefacts and people/nature	Functions, circulation of people, views, lighting conditions
		Consider psychological reactions of people	Fascination, motivation, cheerfulness
	E-action	Make preferential and aesthetic evaluations	Like-dislike, good-bad, beautiful-ugly
Conceptual	G-action	Set up goals	–
	K-action	Retrieve knowledge	–

Additionally, Kim and Maher (2008) developed a coding scheme with five categories and three levels of spatial cognition; 3D modelling and gestures where included in the Action level, perceptual activities at the perception level, and set-up goals and co-evolution at the process level. The aim of this research was to examine the effects of TUIs on designers' spatial cognition through a comparison of the designers using TUI with 3D blocks and of designers using GUIs on a desktop computer. The particular research concluded that designers utilising 3D blocks were immersed in the design model, they perceived more spatial relationships while they spent more time relocating 3D objects. Moreover, the designers restructured the problem and reflected and modified the design task when utilising TUIs. The protocol analysis in the particular case was based on

Suwa, Purcel et al. work (1998) and it was adapted to accommodate the research focus, regarding interactions with different digital and tangible means, collaboration processes among the participants, perceptual activities and their enhancement with the use of technology.

4.4.2 A Review of Mapping The Protocol Stages

The final approach that was considered for the protocol analysis is based on mapping the design process during conceptual design with the aim being the identification of the conceptual activity stages for built environment multidisciplinary professionals (Austin, Steele et al. 2001). The studies included three test teams that were asked to design a building element, a modular window system. The participants recorded the studies' stages and the segments were categorised according to a conceptual design protocol that was developed before the studies (Macmillan, Steele et al. 2001). The duration spent in each design stage and the stages interdependency was the focus of the analysis, which led to the creation of larger design stages' clusters and allowed further conclusions on the iterative nature of the design process applied for the built environment (Figure 4.15).

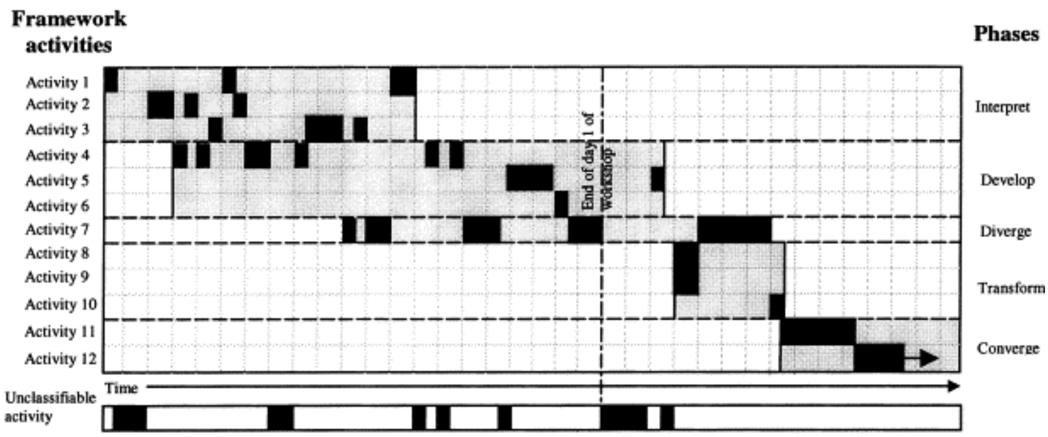


Figure 4.15 The design activities outline according to time spent on each of them (Austin, Steele et al. 2001), pp.216

The common characteristics of protocol analyses and of activities mapping include the segmentation of the videos into distinctive segments according to subjects' intentions within the duration of the studies. Furthermore, each approach is analysing the experiments according to a particular research perspective, which is design cognition, design stages or effects of technology on the design process. Visualising the right type of information is essential for showcasing the research objective each time and the common parameter among the different approaches' charts is the time spent for each activity.

4.5 Data Analysis Methods Applied for the Three Studies in Chapters 6-9: Protocol Analysis

4.5.1 Segmenting the Three Studies Protocols

The protocol analysis applied during this thesis for researching computer mediated conceptual collaborative design initiated with the segmentation of the entire study video recording (protocol) into smaller units (segments). Design protocols can be segmented either according to subjects' verbal events like pauses, phrases and intonations (Ericsson, Simon 1993) or according to subject's intention and to the theme of the content (Suwa, Tversky 1997). For this research the latter approach was the most suitable because it was capable of encapsulating the essence of collaborative design interactions (Suwa, Purcell et al. 1998); thus, the division of the segments was based on "the statements made to build a representation of scientists mental operations" (Dunbar 1995).

The current research followed protocols suitable for analysing TUIs and synchronous collaboration among multiple participants (Gu, Kim et al. 2011), protocols on cognitive actions during design processes (Suwa, Purcell et al. 1998) and protocols on function-behaviour-structure model (Gero, Mc Neill 1998). The segments' division was case depended and the categories in which they could be divided were determined by the research scope (Gero, Mc Neill 1998).

Regarding protocols segmentation and application of codings for each segment, Gabriel and Maher (2002) describe that "a more traditional way of developing coding schemes was by segmenting protocols. Subsequently, categories were developed after carefully reviewing the segmented protocols and coding each segment under a single category only (Purcell, Gero et al. 1996). A more recent method, as cited by Purcell, Gero et al. (1996), is the potentially richer approach of using the 'grounded theory' by Glaser and Strauss (1967) which allows for multiple coding of the single segments." For the purpose of the research and thesis, the more recent approach is applicable and suitable for describing the complex multidisciplinary team interactions.

Importantly, due to the multidisciplinary nature of this research where multiple participants were monitored, each segment was part of different levels and categories at the same time, as followed by the methodology from Purcell, Gero et al. (1996), Gabriel and Maher (2002) and Gu Kim et al. (2011). As Gu Kim et al. stated, "The protocol data comprises the designers' conversations, gestures, and interactions rather than the designers' verbalisation of their thoughts as in the think aloud method. Such collaborative protocols provide data indicative of cognitive activities that are being undertaken by the designers, not interfering with design process as a natural part of the collaborative activities”.

4.5.2 Actions Coding Applied for the Thesis in Chapters 6,7 and 8

The segments of the three studies’ video recordings were coded/categorised according to three levels, including physical level, perception and concept level and collaboration level. The purpose of these levels was to provide answers to the research questions, regarding the participants’ interactions among them and with the physical and digital media, the effect of using Microsoft PixelSense to the participants’ cognitive, conceptual and perceptual actions and the general evolution of the design processes in different studies’ contexts. **Importantly, during Chapters 6, 7 and 8 thorough descriptions of the evolution of the studies are provided. These descriptions or narratives are a summary of the data utilised for the protocol analysis that eventually provided the necessary information regarding the impact of the CDSP and the computational design tool on the design teams collaborative, cognitive/conceptual and physical actions. Finally, chapter 9 presents a comparison of the three studies, thus proving the effectiveness of the intended use of the CDSP and the computational design tool.**

Table 4.7 Thesis coding scheme

Levels	Categories	
1. Collaboration	• Cognitive synchronisation	Argumentation and negotiation
	• Workflow driver	Decision making
2. Perception & Concept	• Perceptual Activities	Focusing on new or existing features
	• Set up Goals	Goals on new and existing functions
	• Co-Evolution	Brainstorming
3. Physical Actions	• Sketching/ Drawing	Drawing, importing images, inspecting elements,

The three main levels that were applied for coding the three studies’ segments are presented in Table 4.7 and these include physical actions level, focused on drawing/sketching both with physical and digital means and the collaboration level including the categories of cognitive synchronisation, ideas clash and the workflow driver. Importantly, the concept and perception level focuses on setting goals and making decisions and on perceptual activities when re-examining existing features and relations. The segments focused on physical perceptual and conceptual actions are adapted from Suwa, Purcell et al. (1998) while the collaboration level is adapted from Gu, Kim et al. (2011) and Gero and NcNeill (1998).

The first level of Collaboration has two additional subcategories, the cognitive synchronisation and the workflow driver. These subcategories reflect participants' collective cognition, with C-Action representing the construction of a shared understanding among the design team and G-Action translating the gestures utilised for non-verbal communication and body language. Furthermore, N-Action presents the negotiations among studies' participants, and the communication of different and contradicting ideas and viewpoints for moving forward the design process. WDe and WDn Actions are the decisions related to existing and new features accordingly (Table 4.8).

The second level of Conceptual and Perceptual Actions refers to actions of setting goals, attending to visuo-spatial features of sketches, drawings and any other form of depicted or written information and of co-evolving of ideas between the participants. Setting up goals or G-Action refers to the moments where the participants are deciding about the way they want to progress and, as a result, set aims. P-Actions are the perceptual ones where the participants are focusing on existing or new relations between features of their work, data and information. Pc-Action is about comparing elements while PF-Action and Po-Action are identifying the segments of problem finding and of organising various elements accordingly (Table 4.8).

The Physical Actions level corresponds to motor activities produced while interacting with materials, design media, drafting tools and physical and digital interfaces. These actions are related to physical depictions on paper or on TUIs/GUIs and there are four types of actions. The first one, D-Action, is about drawing and sketching, making depictions, work with pictures and layers and use the relevant options like rotating and scaling, starting a new canvas or a new depiction, regardless of the physical or digital nature of the medium. I-Action is about importing pictures and it is a motor action applied with the PixelSense. L-Action is on focusing inspecting and looking at elements; these include plans, drawings, sketches, screens, the design brief or any other type of information, i.e. printouts of maps and documents (Table 4.8).

Two additional levels, the Not Applicable (N/A) and Moderator, are utilised to distinguish actions that are not related to the above levels. The N/A level presents the time when the participants are getting ready to start, or they are testing equipment (Warming-up category). Furthermore, due to the use of highly technical equipment there were problems at times with the hardware or the software during the studies; during these cases the moderator provided technical assistance and solved these problems for smooth continuity of the studies. The acknowledgement of the technical problems was essential for the development of the digital conceptual design application. The level corresponding to Moderator Actions includes the introductory slides with the presentation of the design task and the points where participants are asking for clarifications on the design task, the physical and digital media and the design brief. Finally, PP-Action represents the moments where the moderator was promoting the process of the study group (Table 4.8).

Table 4.8 Studies action categories

Levels	Categories	Names	Description
Collaboration	Cognitive Synchronisation	C-Action	Shared Understanding, Shared Representation
		Ge-Action	Gestures and Body Language
		N-Action	Negotiation
	Workflow Driver	WDe-Action	Workflow Driver: Decisions on existing features
		WDn-Action	Workflow Driver: decisions on new features
Concept & Perception	Set-up Goals	G-Action	Goals on new function / Goals on existing functions / Goals following the objectives
	Perceptual Activities	P-Action	Focus on existing or new features/ relations
		Pc-Action	Focus on comparing elements
		PF-Action	Problem Finding
		Po-Action	Focus on organising elements
	Co-Evolution	S-Action	System Brainstorming, System Analysis
Physical Actions	Sketching/ Drawing	D-Action	Draw a line / Work with layers / Draw on pictures or maps / Rotate a picture / Scale a picture / Delete or clean canvas / Start a new canvas
		I-Action	Import Pictures/ Documents
		L-Action	Inspect design brief/ screen/ plan/ layout

Levels	Categories	Names	Description
		Other	
N/A		Problems with Software	
		Warming up	
		Clarification	
Moderator		Introduction	
		PP-Action	Promoting Process

4.5.3 Protocol Analysis: Software and Process

Transana was the preferred software for analysing the studies' results and the applied version was the 2.60 (Figure 4.16). The particular software allowed for transcribing and analysing video recordings/protocols by applying a well-structured method for getting access to these results. Transana can facilitate the qualitative analysis of a video or audio/pictures of a study and through the analysis of these recordings it can quantify that information according to the amount of time spent on each action. Additionally, this software can assist with visualising actions progression in time and it constructs comprehensive visualisations of that data.

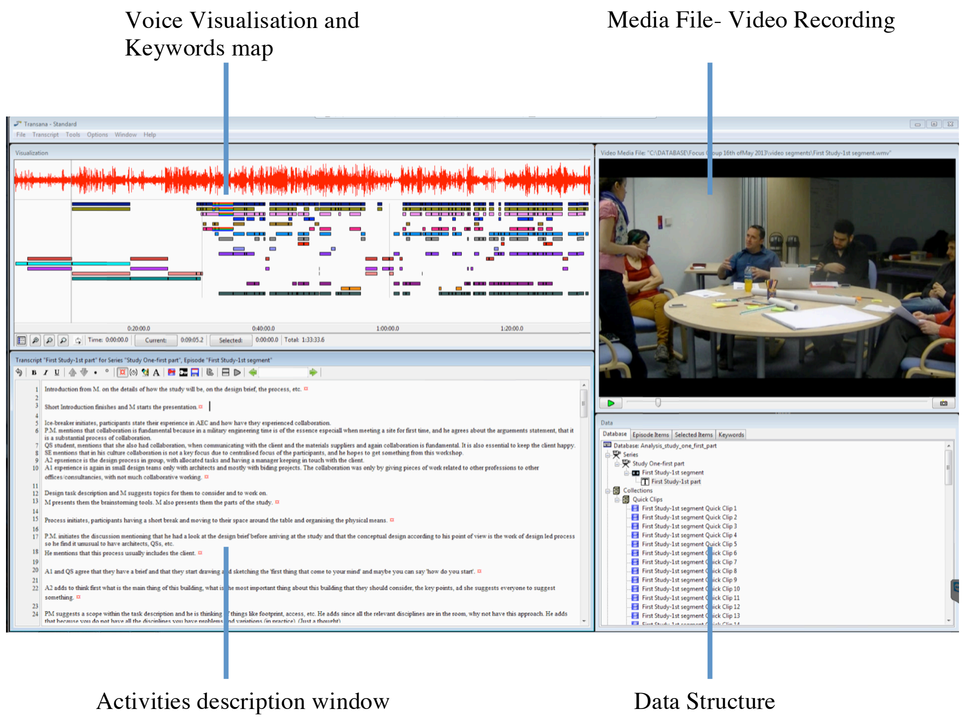


Figure 4.16 Transana interface (media window, description, segmentation and keywords map)

The method for obtaining the results initiated with transferring the whole study duration of the recording to the computer and making separate clips according to the stages of the study. Afterwards, the transcription of the clips took place followed by linking positions in the transcript to the corresponding positions in the media file, effectively connecting the recording to the script, as instructed by the software directions (Woods, WCER 2014). Keywords were assigned to the recording instances and visualisations of the quantified data can be produced. The steps for preparing data for analysis in protocol studies were also described by H. Salman (Salman 2011), pp.223, and (Salman, Laing et al. 2014). She identified six steps, dividing the recordings into clips to get the right duration of the active time, transcribing the think-aloud processes, assigning clips by time stamping, segmenting arbitration, data coding by assigning keywords and coding arbitration.

For the purpose of the particular research the structure has been adapted to comply with the research aims, which is to identify the process the participants follow, identify time spent during activities and the types of activities that take place during conceptual design. As a result, the first task was to separate the whole duration of the recording into the three parts of the studies according to their structure and import these clips to the software. The studies structure is presented in Figures 4.5-4.7 in Section 4.3.1.

The second task was to describe the dialogues, the events happening during the study and the actions of the participants and of the moderator. The group work had certain characteristics regarding collaboration and perceptual activities and the verbalisation of their ideas was occurring because of the interactions among the participants, the exchange of their ideas and the conceptual design evolution. Additionally, it was important to monitor the different types of professionals contributing at the different points of the discussion.

The third task was to segment the transcription according to the different themes, as described in Section 4.5.2 on protocols' segmentation. These smaller units were assigned to the video recordings according to the time codes (the parts of the video displayed), thus maintaining a close connection between the raw data and the analysis. The keywords developed for coding the different action categories were applied to the segments following the closest description of the actions.

The last task was to get the analysed data, which are the keyword maps that presented the types of actions in time and the collection reports that summarised the analysis and provided number of segments and duration for each action category, and to either draw conclusions straight from them or to import that data into spread sheet software for further analysis. A summary of the coding process including the description, time segments and applying keywords is presented in Table 4.9.

Table 4.9 Transana coding extract

Segment Number	Duration	Actions Description	Clip Keywords
49	Time: 1:05:41.5 - 1:06:42.6 (Length: 0:01:01.0)	A2 argues that too much glass might be a problem and PM adds that too much glazing can cost a lot and might cause problems to the construction. A1 replies that you can shadow it, thus providing a solution to the problem.	Collaboration : C-Action Collaboration : Ge-Action Collaboration : N-Action Concept and Perception : P-Action Concept and Perception : PF-Action Concept and Perception : S-Action
50	Time: 1:06:42.6 - 1:07:50.9 (Length: 0:01:08.3)	PM talks about problems with glare and A2 states that some rooms can have controlled glass surfaces while others can be more or less glazed depending on the heat needs and working needs. QS agrees and further comments on it.	Collaboration : C-Action Collaboration : Ge-Action Collaboration : N-Action Concept and Perception : G-Action Concept and Perception : P-Action Concept and Perception : PF-Action Concept and Perception : S-Action
51	Time: 1:07:50.9 - 1:08:17.0 (Length: 0:00:26.2)	PM discusses the position of the entrance, he thinks that they should change it and A2 agrees on that. A1 found some more ideas on the internet.	Collaboration : C-Action Collaboration : Ge-Action Collaboration : N-Action Collaboration : WDe-Action Concept and Perception : G-Action Concept and Perception : P-Action Physical Actions : I-Action Physical Actions : L-Action

4.6 *Data Analysis Methods Applied for the Three Studies in Chapters 6-9: Actions' Mapping*

The data utilised for actions' coding through Protocol Analysis were also valuable for mapping the design process. This approach was developed by Austin Steele et al. (2001) and Mcmillan, Steele et al. (2001) for identifying and understanding the phases and activities during conceptual stage, as it was further analysed in Section 4.4.2. The data utilised for analysing the studies consisted of video recordings of the whole duration of the studies, which present team members conversations, interactions and gestures, and any type of additional information required to promote design thinking

(Stempfle, Badke-Schaub 2002), like sketches drawn from the participants, excel spreadsheets with their calculations and information found on the Internet.

For this particular research, the mapping analysis was focused on participants' physical actions, on perceptual and conceptual actions and on collaborative processes according to the steps presented from the Conceptual Design Stages Protocol. As a result, a map of the conceptual activities was created for the purpose of showing the design process and evolution within studies' duration, for providing insights in order to understand the design development that the teams are following and for presenting the levels of adaptability to the Conceptual Design Stages Protocol.

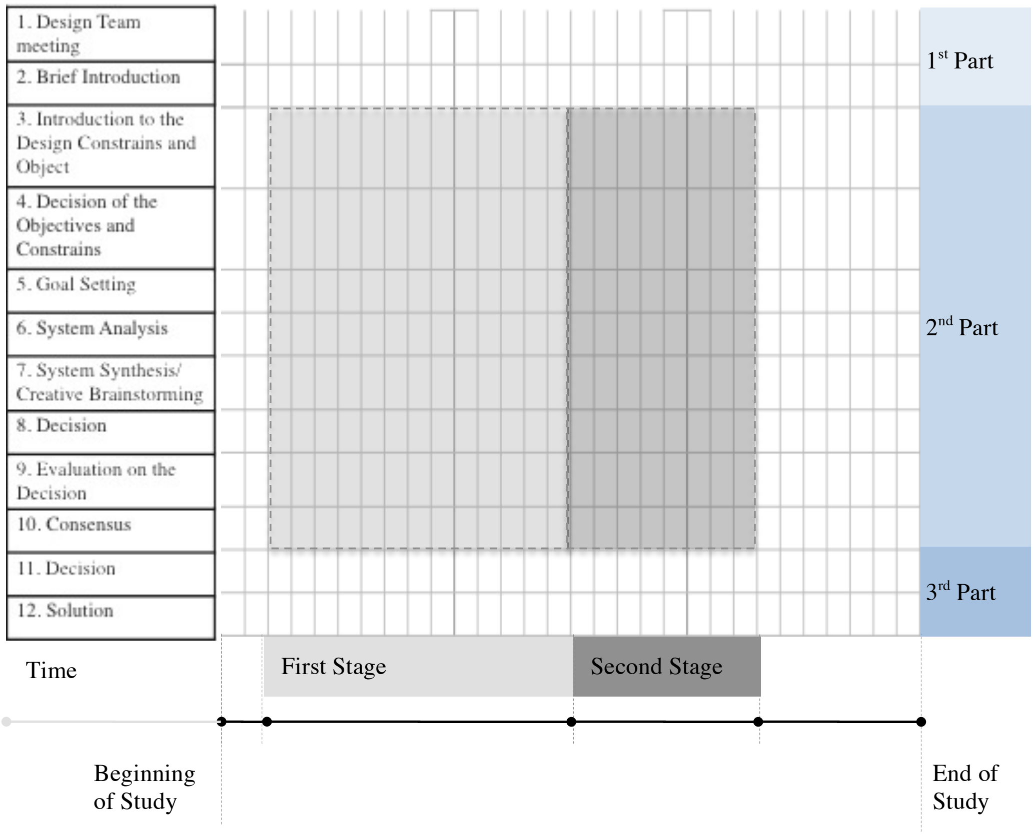


Figure 4.17 The tool for mapping the design activity

The vertical list describes the activities according to the Conceptual Design Stages Protocol as presented in Figure 3.6, Section 3.2.2, and the numbers on CDSP diagram are the same with the vertical descriptions. The darker areas within the graph represent the first and second stage where the physical design mediums and digital media are used. The horizontal axis presents the evolution during time and within the different parts and stages of the study (Figure 4.17). The squares represented a unit of time and the filled squares showcased the occurring activity and that particular unit. Importantly, even though the Conceptual Design Stages Protocol was tested in studies 2 and 3, it was critical to monitor the process of the first study according to the same table in order to identify the progress of the study.

4.7 *Visualising Data*

It was important to consider the ways of visualising the collected data derived from the research studies. The data visualisation methods make the data easier to understand (Krum 2014). By applying methods from the fields of computer science, statistics, data mining, graphic design and visualisation it is possible to understand and visualise complex and changing data (Ware 2012). The knowledge from different disciplines complements one another to provide a full and informed visualisation. Data mining is important for solving problems by analysing data already present in databases (Witten, Frank et al. 2011). During the data mining process meaningful patterns in data are discovered and the process can be automated. Information visualisation supports the visual representations of abstract data often through software-based processes. By bringing together the different approaches and focusing on the effective communication of the meaning then the data conveying visualisations can be easily understood and adapt to information changes.

The purpose of data collection and display is to further support analytical tasks, contrasts and comparisons among the data, thus allowing cognitive conclusions to be drawn (Tufte 1983). Tufte explained that the graphs should describe complex ideas and information in a clear, efficient and precise way. Furthermore, it is important for the graphical displays not only to present data but also to trigger cognitive activities from the viewers, to turn large amounts of data into a coherent set, promote easier comparisons among data and, essentially, keep the graphs and displays connected to the descriptions.

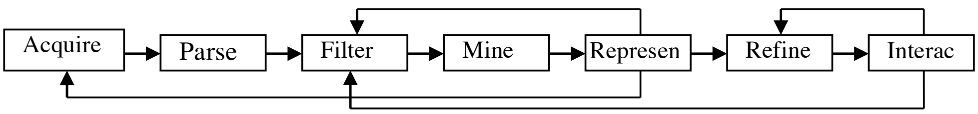


Figure 4.18 Interactions between the seven stages of data visualisation, adapted from Fry (2008), pp.15

According to Fry (2008) seven steps are required to reach the data visualisation (Figure 4.18). These steps comprise out of the data acquiring, from different resources, parsing the information by organising them into categories and giving them a structure, and filtering the information that is not relevant. After the initial organisation, data is mined to provide a mathematical context and is transferred to a visual model for representation. A refinement assists at improving the representation and eventually an interaction is inserted to control the visible features. Data visualisation is a highly iterative process that demonstrates the interdisciplinary approach including programming, visual design and mathematics.

4.8 Summary

This chapter introduces the part of the thesis that tackles the third objective of the research aim and the relevant methodology and methods. A mixed methods approach is used throughout the research, with qualitative methods providing further information on the current paradigm in the AEC industry, regarding problems and requirements arising during conceptual and collaborative design. The qualitative methods include semi-structured interviews and design and construction teams' shadowing presented in Chapter 5 that further support the literature review in Chapter 2.

Moreover, quantitative methods are employed for facilitating and testing both the current paradigm of conceptual design and the proposed Conceptual Design Stages Protocol. Three studies are employed for enhancing the understanding of the design process adopted by design teams. The first study is the exploratory one, where the professionals follow a conceptual design process based on their previous knowledge and the current paradigm in AEC industry. The second study is the one that tests the CDSP and the developed computational design tool. Eventually, the third study not only tests the optimised CDSP and computational design tool but also incorporates the transfer of the design information to Revit.

Chapter 4 also presents a review of relevant research on monitoring collaborative design and observing multidisciplinary design teams. Afterwards, the methodology and the three studies' components are established. The studies components are comprised of:

- The Design Brief
- The type of participants for each study
- Design mediums and digital media to be used for each study
- Monitoring methods and the aspects to be examined
- Anticipated outcomes

The methodology for analysing the collected data is reviewed and the specific methods applied for the three studies are thoroughly presented. These methods include the protocol analysis and the activities mapping and they are the most suitable methods since the first approach allows the identification of physical, conceptual, perceptual and collaborative actions during the studies, while the second approach maps the design process of the studies within time.

Protocol analysis is applied with a particular qualitative and quantitative analysis software; the software used for analysing the studies is the Transana, which allows for transcribing and analysing video recordings of the studies by applying a well-structured method. The video recordings of the studies are imported in the software, divided in parts and stages according to their structure (as presented in Figure 4.5-4.7) and afterwards they are segmented into smaller units (segments). The recordings that showcase the participants' actions are segmented according to the theme of the content (Suwa, Tversky 1997). Furthermore, these segments contain the actions that the participants of the studies are undertaking, including collaboration, perceptual and conceptual activities and physical actions. Table 4.8 presents is great detail the actions' subcategories.

An additional method used for showcasing the progression of the studies is the activities mapping, where the progression of each study is mapped according to time and according to the process described in CDSP. The mapping tool that is used for all three studies is presented in Figure 4.17.

Eventually, collaboration, perception and concept evolution among multiple disciplines and participants can be monitored, thus answering the research aim on the effectiveness of the intended Conceptual Design Stages Protocol. Furthermore, the impact of computer mediation on the concept stages can also be monitored and differences with the use of physical means can be acknowledged.

5 Interviews and Shadowing Feedback

Chapter 5 presents the outcomes from eight semi-structured interviews and from two teams' shadowing. The number of the involved participants was illustrated in Table 4.5 while the timing of the interviews and shadowing was demonstrated in Figure 4.4. Face to face interviews with eight experts of the AEC industry provided further support to the necessity for an organised approach straight from the beginning of a project for exchanging the maximum amount of information and incorporating information and feedback from all the potential stakeholders of a project. In addition to the interviews, a shadowing process of two large multidisciplinary design teams took place for further evaluating and refining the interviews feedback and eventually comparing them against the research questions and the developed methodologies. The role of interviews and the teams' shadowing within the research was merely supportive of the main research argument and they were not the key focus of the research.

5.1 Interviews

The interviews were employed with the intention to conduct research on identifying the current paradigm in conceptual design for design professionals. Data saturation was the preferred method for evaluating the results and for deciding the stopping point where there was no new information being added to update the questions (Glaser, Strauss 1967; Guest, Bunce et al. 2006). Initially, a minimum sample size for initial analysis was specified, which decided the point where no new information was altering the structure and content of the questions and that was the stopping criterion (Francis, Johnston et al. 2010). The particular point was reached after the first three interviews; cumulative patterns' saturation revealed that by the third interview the thematic codes had been developed and the formation of a semi-structured interview allowed for small variations between the different disciplines. Eight interviews in total were employed during which a number of shared beliefs and ideas were discovered and common patterns were identified until data saturation was achieved.

The questions were aimed at identifying conceptual design for their practice, finding details on the problems that professionals face during collaboration, the types of disciplines usually involved during conceptual design and the type of information required to move forward the design process. Furthermore, the team dynamics among the design team members and professionals and eventually how all these decisions were transferred into digital information and into BIM were also part of the questions, in order to verify with the relevant literature review (Section 2.1 and 2.2). The questions were sequentially structured to allow the interviewees to reflect on their previous answers and to keep an effortless flow of information in a way that the data in their totality would be formulated into educated categories (Redmond, Hore et al. 2012).

The participants shared certain characteristics and these included their professional focus with all of them being AEC professionals and practitioners from major firms with substantial experience in the sector. The types of professionals interviewed included experts from key professions of the AEC industry, namely, architects, a contractor, a building surveyor, quantity and building surveyors. Regarding the representatives' affiliations, the firms were internationally recognised and provided a range of practices, from architecture, construction, infrastructure, services and property.

5.1.1 Interviews Context and Procedure

The first few interviews took place after the completion of the first study while the greatest number of them was after the second study. The initial ones provided the required wider spectrum for understanding of the problems and issues in the AEC industry for concept stages and multidisciplinary collaboration while the rest of them further supported the initial feedback.

All interviews initiated with an introductory presentation on the scope of research and its relation to the AEC industry, for the purpose to provide coherence and to present its application for the industry. The presentation included the reasoning behind the research, the purpose of focusing at the early design stages, the application with BIM and the research methodology regarding the development and testing of the CDSP. Furthermore, the stages of the protocol were presented together with images from the first study, for the reason of showcasing an example and brief explanation of the studies. The presentation concluded with a final slide that included the questions of the interview and the template of the presentation is attached in **Appendix C.**

5.1.2 Interviewees Sample Selection and Description

The selection of professionals considered within the sample frame was based on the types of involved professionals within a project and the significance of their relevant decisions according to different types of procurement (Figure 5.1). As a result, the interviewed professionals included mostly people related to design and cost decisions. Importantly, the range of interviewed professionals had different roles and positions in companies' structures and within the AEC industry, as presented in Figure 5.2.

The interviewees were comprised among others from three directors, a managing director from a multidisciplinary company with a focus on quantity surveying, project management and construction-design-management (CDM) co-ordination. Furthermore, the interviewees comprised out of a business developer director from a prominent infrastructure, support services and construction, and a construction director from a major construction company. The interviewed practitioners were all senior consultants and some of them partners in the consultancies with long experience in the sector. The reason for addressing both directors and senior practitioners was to shed light to the multidisciplinary design and construction processes and to the stages where the professionals are asked to work within the silos. The interviewed professionals were based both locally (Scotland) and within the country (UK) with projects ranging from a local to global scale.

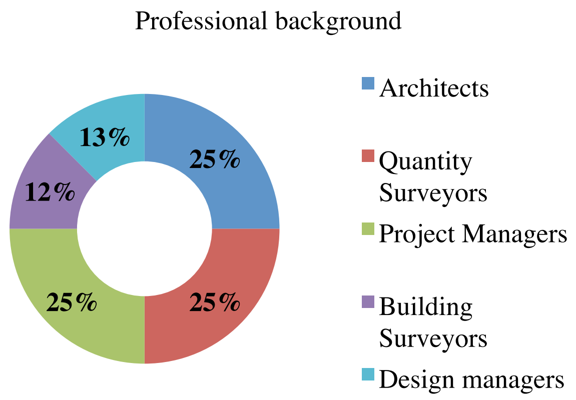


Figure 5.1 Sample frame of interviewees

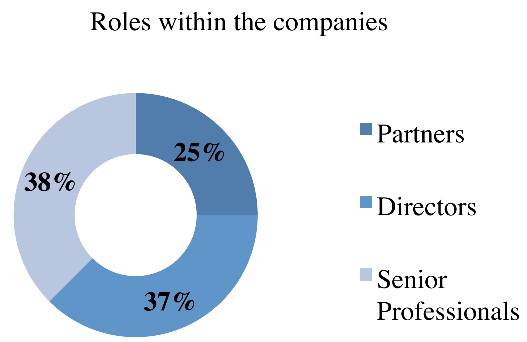


Figure 5.2 Sample frame according to industry roles

5.1.3 Conceptual Design Process

The first question was focused on the process that the participants follow for achieving consensus during conceptual design. The process identified from all the interviewees regarding concept stages depended on the type of project and, as a result, on the procurement process. Typically, the projects initiated with handing the design brief to the architects, either straight from clients or from the contractors. Afterwards, meetings followed for checking designs according to designs database within the organisation. External consultants and specialists were appointed during these meetings, like teachers for educational projects and doctors and nurses for healthcare. Design development was the subsequent stage supported with intense electronic communications for exchanging drawings and ideas, and promoted with face-to-face meetings for establishing central decisions and achieving an agreement among all stakeholders. During these meetings the discussions would take place on top of plans' printouts. Eventually, feasibility stage would conclude with the designs that achieved team consensus, that they were proved for their buildability and that they were within budget. Quite often, different solutions needed to be developed for the clients to choose according to their priorities and the series of stages would encompass a number of iterations between the different involved professionals until the required level of project detail would be achieved.

The client would typically introduce the design brief to the architects, although, more and more architects were no longer the first point of contact, with the building contractors or building partners taking over the managerial role of the project resulting in the architects being involved during the next stage. Another approach applied for developers, included the build up of a business case comprised out of cost effectiveness calculations and residual valuations that would inform on the cost of the construction and the profit estimation. In this case, the involved practitioners from the start of the project would be mainly comprised out of quantity surveyors and less of design focused professionals. According to the cost feedback, clients would decide whether to continue with the construction or not. Afterwards, the architects would initiate with the designs taking into consideration the strict budget, therefore multidisciplinary feedback would ensure that designs were up to brief's standards before the planning submission.

One consultancy representative commented that they used to undertake project launch workshops where all the involved stakeholders participated, a range of decisions was taken and a values' rating on project features was additionally undertaken. The needs against wants were being balanced during these workshops. The stakeholders were asked to prioritise against each other aspects like additional storage, temperature control, acoustic privacy or increased office space and the results were stored in a developed matrix. Establishing priorities and values according to client enabled in these cases a quicker approach to the feasibility stage.

Other professionals reported that according to their experience, they tended to work in silos, with each and every type of professionals' teams having a solution to the project, for example, the architects having a design solution, the mechanical engineers producing their solution and construction engineers producing evaluations for the structure. In this case, it was usually the architects who were getting the information from the clients about the project and after the various aspects of the project were clarified with the client, with the rest of the professionals used to come on board at a later stage. **It was acknowledged that the greatest feedback provided among different disciplines and the client at that stage the better the produced designs and the more accurate the prediction of the project.**

5.1.4 Conceptual Design Stage Problems

The second question was on the problems that the participants have experienced during conceptual design. The problems monitored during these stages concerned the repository of all information on a project, its location and the access of the relevant people to the drawings. Furthermore, benchmarking was also essential for making sure that the project is cost value according to competition. In many cases, the project's budget was considered an important factor, while other projects might focus on environmental conditions or sustainability aspects. Based on that focus potential issues might arise in case design brief did not cover all the compulsory aspects or if functionality did not meet the requirements.

Additional problems occurred during this process, with one of them being changes from the clients on the design brief or changes to the types of procurement, thus leading to delays, miscommunications and differences in budget. Clients' role was recognised of great importance since it is the one providing the requirements and the budget for a project and the more informed the client the smoother the collaboration among all stakeholders could be. Informed clients would be able to set standards for the type of structure, the budget, the regulations it should comply with and eventually would provide a very detailed design brief. Frequently though, clients were not informed and they were looking to generate ideas during the project progression, expecting from the employed designers or contractors feedback on the project requirements. An approximate estimation of this difference divided the clients in 50% of informed ones and 50% of uninformed ones. The aforementioned problem was related to another important one, the lack of cost control. A disorganised design brief could lead to a number of problems, including issues with collaboration, with teams' organisation and great loss in time and costs.

An additional reported problem was the fee recovery, since feasibility stages are frequently part of a competition process and this particular stage of conceptual work is not fee covered. As a result, there was a hesitance for the engaging teams to work hard on that stage, due to the uncertainty of the project commission. Moreover, teams were asked to work against time, since most competitions had strict deadlines, which, together with the aforementioned restrictions, led to creative design repetitions according to successful previous cases of similar projects. Another potential reported issue was the stage at which each consultancy would be employed, for example, quite often contractors were engaged at much later stages, that resulted in time loss in communicating and distributing projects' responsibilities, or in different cases problems might arise from differences between appointed consultancies, regarding cost and concept for example.

5.1.5 Important Information for Conceptual Design

The third question was concentrated on the type of information and processes required for assisting the design to move forward. In most cases the importance of establishing the design brief at the beginning of the project was the most important feature, with specific details and established size, site location, ground condition and surveys, for understanding the condition of the site and of the ground conditions. Determining these aspects as early as possible was reported as essential since they could often lead to big costs. Trying to get the building layout fixed as early as possible and finding a chance to get the client to agree, followed by the structural process straight after were also confirmed fundamental requirements for making sure that the project was not following a process that nobody agreed on. Having regular reviews for ensuring the project was on the right track was also crucial, while during these meetings greater details on M&E systems and structural elements were being added to the project. A very interesting observation on the design brief was the reply of an architect who mentioned that the design brief is fixed once the project is built, overstressing the flexibility required for the design brief and the number of changes it might need.

One of the consultancies was focusing on projects' constraints that were decided through a collaborative consensus among all stakeholders, often supported by the creation of mock-up spaces of the proposed project. According to the same consultancy, operational adjacencies were usually the greatest factor for deciding on projects' constraints, regarding aspects like fire exits, storage spaces, workshops and classes for educational projects. On the other hand, certain type of space adjacencies were required for healthcare projects. Other professionals replied that the required information was contract depended and the most important part would be to involve a project manager to run the project from the beginning of the feasibility stage to the delivery of the project, with an architect and a client representative to ensure the smooth continuum of the project.

5.1.6 Conceptual Design Team Dynamics

Finally, the last question was on the organisation of team dynamics and the type of involved professionals. These dynamics were depended on the scale of the project, with contractors undertaking the management of a project while in smaller scale projects this role was applied to the design team. The multidisciplinary teams were not often employed according to the feedback from the different participants. According to the contractors' feedback, during the launching workshops the whole design team usually took part, including the design manager, the project manager and the client representative. Stakeholders and end-users were often also appointed to participate and based on the feedback of these workshops changes were being made to designs. For typical large-scale projects, the required practitioners would be architects, mechanical and electrical engineers, quantity surveyors, increasingly input was required from statisticians and ecologists, roads and transportation experts and civil engineers especially for feasibility stages decisions.

The triangle of time-cost-estimation was also considered an important tool for prioritising clients' wishes and needs. Based on that information, the procurement process could be decided; therefore the most suitable type of team organisation could be identified and applied. In case cost would be the most important priority, a quantity surveyor would have to guide the process, while if the priority would be the design then this role would go to an architect. As a result, project team consensus would be achieved in agreement and following clients' priorities, hence projects' dynamics would adapt to the project values each time.

Essentially, on-time feedback from different professionals and stakeholders frequently resulted to fewer complaints and miscommunications, thus indicating a smooth project continuation with less unexpected costs and design iterations when a cooperative work is undertaken.

Regarding transferring these decisions to BIM, it was recognised that opinions were contradicting; some practices worked on BIM or Building Information Warehouse (BIW) type of software, while other professionals considered that BIM was considered an additional cost for the clients and they would argue not to include it in a budget since services clashes for example was their standard expectation from the engineers in the first place. However, BIM was recognised as a tool that might bring back the management and lead of a project to the architects.

5.1.7 Semi-structured Interviews Conclusions

Due to the semi-structured nature of the interviews, the questions varied according to the feedback in each case, making sure the core of the interview was being kept intact. The interviews concluded with a comment from the participants on the topic of the research. One of the interviewees recognised that project decisions taken earlier on were fundamental, but they would still need to change, due to the effect of cost and the potential changes suggested from planners, leading to differences between the feasibility and delivered project. Furthermore, the size of the project was also a substantial parameter for the feasibility stage, with large-scale projects requiring greater amount of information for ensuring that the project managers get all the details of the project, while smaller projects tended to allow a more hands-on experience and thus were easier manageable.

The interviewed quantity surveyors reported that collaborative design at feasibility stage would require time commitment from the involved professionals and most importantly would require an informed client. They recognised though that the current paradigm would waste resources creating drawings that would need to change after the multidisciplinary and clients' feedback, while the collaborative approach would not necessarily require long time involvement and the decisions taken at that stage would speed up the process for the continuation of feasibility and advanced design stages. Furthermore, a common recognisable problem was that the uninformed clients would spend the least amount of money on feasibility studies, which was considered by all of them the most important part of work where the most important decisions were taken.

5.2 Shadowing design and construction teams

The process of shadowing design teams became part of the research after the interviews had initiated. Two large multidisciplinary teams were shadowed for two to three hours each one of them approximately. Detailed notes were taken during these meetings that described the activities of the participants, the insights and thoughts on the collaborative activities. The shadowing process was focused on interactions and communications among the team members and not on the actual project that they were discussing.

Newby (2009) refers to observation as a learning process, which is further categorised by McDonald (2005) into three different types of shadowing, including experiential learning, recordings of behaviour and "seeing the world from another perspective". The first two approaches are used during both of the shadowing processes and they are descriptively analysed. Experiential learning is the type of shadowing that is suitable for initial stages of investigations for building up background knowledge, and within the particular research the initial purpose for conducting shadowing was to evaluate the interviews feedback and refine the information regarding multidisciplinary design. Furthermore, behaviour recording was an additional monitoring aspect for the purpose of analysing teams' communications, interactions, collaborations and potential problems that might occur during multidisciplinary team meetings. The two shadowing processes are afterwards described.

5.2.1 First Shadowing Process

The first team shadowing was on a renovation project of a building in Aberdeen, UK, and the involved participants were an architect, two contractors, a mechanical engineer, a project manager, a client representative, a site manager and a technician. Project manager was the one managing and moderating the meeting with input and feedback from the rest of the participants. The meeting took place in one of the rooms that was being renovated in the construction site and one wall of the room was fully covered with a time management plan, a Gant chart, representing activities and their timing within the project. Each professional had a pack of different colour post-its for ensuring the topic distinctions of the feedback on the Gant chart. The researcher in this case was standing behind the group so as not to disrupt or affect the process, while taking detailed notes.

The participants initially went quickly through the whole process, bringing everybody up to date, with all the relevant professionals describing their parts of the work. The discussions on each aspect that was part of the time plan resulted in comments, arguments and eventual solutions, and the final update was noted with post-its on the printout of the time plan, thus updating the process of the project. The project manager was taking the team through the different points that required information, from the ground floor works to the second floor ones, referring back to the project commissioning and finalising the times and actions to be followed by the contractors. It was also the same person who was keeping detailed notes of all discussions, ideas exchange and changes in plans and time-schedules. Argumentations about the time delivery of different parts of the project were occurring, but either they were being resolved with adjustments in other workloads or with resonance about the unexpected difficulties and reorganisations of the workloads.

Depending on the topic of the discussion, the participants were separated in smaller groups. One version of groups was a separation among consultants and contractors and technicians, with the engineers and managers commenting on the time-graph and the more technical people clarifying construction details. Once again, there was no linear evolution, rather the groups were confronting the meeting's topic in a holistic way, moving from one topic to the other, either according to the influence of each part to the other or according to the reservations of each participant regarding their focus on the project. Quite often, the two groups were dissolving and were composing a bigger one, focused around the project manager who was providing directions or asking for further information.

After the first half hour of the meeting, two more contractors joined the discussions. Once again, two groups were formed, with the first one discussing issues with the works evolution for the ground floor gathered around the project manager. Apart from him, the rest of the group members included the site manager, the mechanical engineer and three contractors. On the other hand, a smaller group composed out of the technician, the architect and the client representative, were discussing details on the fist and second floor. Soon after, the first group was dissolved into two smaller ones, the site manager discussing with the project manager and the rest of the participants negotiating their ideas. During these processes, the key issues with the project were questioned by the P.M. and the answers were coming either from contractors or from the engineers and designers. The participants had varied distance from the time management printout, either very close for commenting and putting post-its with comments, from some distance for observing the totality of the project or from afar, with the last case focusing less on the time schedule and more on technical difficulties and other discussions.

Following the description of the more generic issues of the project, the participants related especially to time delivery of the different parts moved forward into discussing details of the project, like fixings, partitions and furniture. The project manager was moving the topics forward and the replies and discussions assisted in the evolution of the solution space. These answers were coming mostly from the contractors at that point and during these discussions further issues were arising, related to the simultaneous nature of the works progression and the decisions needed to be taken regarding the actions succession. Eventually, the project manager concluded the meeting by commenting the necessity for fast actions to avoid delays due to unexpected problems that could lead to potential delays in project delivery. The main contractor added up on that comment by mentioning the importance of the structure of the project and urged the rest of the participants to put the maximum effort on it and not "on the looks" of the project. After the meeting was finished, smaller discussions kept going on details of the project where the participants discussed additional details not mentioned during the meeting and also reflecting back to their own experiences.

5.2.2 Second Shadowing Process

The second case of shadowing and monitoring a design meeting took place in Glasgow and it was about an educational project, a school renovation and extension. The involved professionals in this case were the design manager (D.M.) who was also the moderator of the group and the one knowing client's wishes, two structural engineers, two architects, two mechanical and electrical engineers and two quantity surveyors. This time the meeting took place in a meeting room with the participants seated around a large table. The plans of the proposal were on the table showcasing the design solutions and the surveyors had brought a spreadsheet with the decisions and problems for the particular project. The design manager had a checklist that was going through during the meeting, thus guiding the discussions and decisions based on previously reported issues with all of the participants keeping notes during the meeting.

The design manager initiated the discussions and was the person asking most of the questions during the meeting. The initial topic of their discussions was on the building's elevations and the comments were mostly focused on the time required for making the necessary changes in the architectural drawings for a faster estimation from the Q.Ss. The team from the beginning was mostly worried for the delays of the project due to indecisiveness from the client, the desired changes at later and more advanced stage, and the potential drawbacks that would occur due to the facades' formation. After the client's feedback on them The D.M. asked for the price of the project so far as value engineering and not as a final budget that would be sent to the client. Mechanical issues were also discussed at that point since they were affecting the architectural development, followed by problems with the gutters and their connections with the brick panels of the facades. The designers acknowledged the difficulties in communicating with the client and commented “no point fighting since the client is engaged in the façade formation”, which suggested that this part of the brief would have to be developed in close communication with the client.

Regarding the larger number of topics for that meeting, they were resolved quite quickly; such an example entailed the acoustics of the building and the decision in this case concerned getting the quote for the following meeting. Questions were also addressed to the D.M. from various participants, who either provided feedback or suggested the check the topic and provide answer later on. A topic that again took longer to resolve was focused on the foundations of the building and choices of materials for the roof structure; in this case the most important impact for the first issue was the finalisation of the architectural drawings, and in the second case it was the cost of the materials and their engineering, both of them going back to the uncertainty of the client. Quite often, the main difficulty was the time constraints and the pressure to update faster relevant information. Costs increases were also an important topic discussed at that stage and the suggestion for the development of a responsibility matrix followed. BIM integration of the drawings was a complicated topic, since the client required a BIM model but that would led to an increase in the total cost of the project. Similar constraints applied for a BREEAM adaptation of the building. D.M. commented on that, “we will inform them (the clients) that their decisions are translated into costs”.

Once again, short discussions provided clarifications and further actions on topics like number of toilets, additional storage space, getting suitable plans from a fire engineer, predicting space for equipment, costing the structure and eventually informing client for any potential changes. The changes especially on the size of the building were worrying for the civil engineer who was warning for additional costs’ implications due to increase in required parking space and changes in roads. At that point participants were starting getting tired as it was observed from their body language, laying back on the chairs while before they were all focused on the materials on top of the table and were exchanging opinions more actively. The D.M., though, kept them focused on the topics of the discussions and was promoting the ideas’ exchange and collaborations by asking and prompting solutions finding processes. Soon after, the process concluded with the D.M. commenting, “so, that makes it a nice meeting”, and further finalisations taking place on the immediate set of actions with the most urgent one being the architectural drawings completion for delivery to the other engineers.

5.2.3 Teams' Shadowing Conclusions

Collaboration was overall smooth in both meetings, with all the participants trying to resolve the issues that were raised during the discussions. Both meetings were also very intense in the amount of exchanged information and the number of decisions taken forward and they were both guided by project or design managers. What is more, the meetings reflected the process followed during the three studies of the specific research, therefore providing reassurance for a smooth integration of the proposed methodology and CDSP.

Interestingly, the shadowing highlighted the potential problems of conceptual design, with a great risk factor coming from the design brief formation and the clients' wishes and needs. Even though in the second case a value engineering exercise took place in the beginning of the project, for organising the brief and predicting the evolution of the project, a great number of changes happened due to clients' decisions that led to the cancelation of the initial exercise. The particular contract was a Design/Build, which was open to changes and to budget fluctuations, but the resulting delays were becoming business critical.

5.3 Summary

Eight semi-structured interviews and two design and construction teams shadowing with senior professionals of the AEC industry were employed to further support the research argument on the requirement for multidisciplinary collaboration and increased effort during early design stages. Furthermore, the current paradigm of the AEC industry was identified together with problems commonly arising within projects. This information was essential for further assisting in clarifying the research gap, as described in Chapter 2.

The discussed topics during the interviews and the observed ones from the shadowing processes showcased some shared emerging patterns. The most important ones included:

- The greatest feedback provided among different disciplines and the clients especially during feasibility and concept stages, the better the produced designs and the more accurate prediction of the project.

- Working in professional silos and having separate solutions for the different type of professionals continues to be a common practice among professionals.
- Commonly arising problems involve the repository of all information on a project, the location and access of the relevant professionals to the drawings, benchmarking and cost value, miscommunications, changes occurring due to clients' decisions, fee recovery and misinformed clients.
- Multidisciplinary teams' meetings provide the greatest amount of information and are able to take the project forward efficiently and effectively by solving any issues or problems through informed decision making.

Overall, the feedback provided from the qualitative data not only enhanced the necessity for informed decision making and multidisciplinary design work, but also supported the requirement for a process that would be able to guide the teams through structured steps in order to achieve the informed consensus, as proposed by the Conceptual Design Stages Protocol. The information exchanged during team meetings could highly benefit from the application of the CDSP since it could lead to a smooth integration of design decisions and informed decision-making within the context and the requirements of a project. The CDSP aims to systematically, strategically and efficiently bridge different professional viewpoints and to promote an effective and analytical ideation process.

6 Study One

This chapter presents the findings of the first study, which was an exploration on the current paradigm of conceptual design. The purpose of the study was to identify the mechanisms that take place during conceptual collaborative design between different types of professionals by monitoring the steps of the team after they are handed a design brief. Additionally, a questionnaire and a discussion at the end of the study provided the necessary feedback to the process. The questionnaire was focusing on three different aspects, to investigate the prior conceptual design and computer mediation experience, to find out about participants feedback on the process of the study and to identify the difficulties faced during the study.

The particular study provided the practical knowledge on the development of the conceptual design and the steps that a multidisciplinary team is undertaking to reach the conceptual solution and complete the preliminary feasibility stage. This study assisted with specifying the initial concepts of the research, that is the multidisciplinary approach, the computational means and the design process, and provided feedback for further investigations.

6.1 Method: Studies Components

The first study focused on conceptual design processes; it explored the current paradigm of conceptual design when the multidisciplinary approach is applied. During this study the participants tested the contemporary approaches to conceptual design by utilising both physical means and digital technologies. The specific components focused and utilised during the first study are summarised in Table 6.1. The design brief, the introductory presentation and the questionnaires can be found in **Appendix D.**

Table 6.1 First study's components

Design Task	▪ The conceptual design of a building that is going to host research and KTP students of Scott Sutherland School. The building includes office spaces, relaxation spaces and secondary/assisting ones.
Participants	▪ Two architects, a surveyor, a construction manager, and an architectural/structural engineer
Means	▪ Physical means (pens and tracing paper, maps' printouts, pictures, post-its, magnetic board) ▪ Digital means (laptop, desktop, M.S. PixelSense)
Method	▪ The current paradigm of conceptual design
Monitoring	▪ Two recording cameras, a digital camera, questionnaires and end-discussion
Aspects to be examined	▪ Multidisciplinary work ▪ Conceptual design stages ▪ Interactions with digital means ▪ Study's set-up ▪ External conditions
Critical Situations	▪ Multidisciplinary work ▪ Interactions with the TUI
Anticipated outcomes	▪ Technical problems ▪ Identification of the design process ▪ Identification of ways to overcome problems
Ideas for further development	▪ Shared understanding to feed into the BIM model ▪ Improvement of the digital platform ▪ Further theory: the thinking hand as a tool for communicating ideas
Outputs for informing 2nd study	▪ Differences within physical actions during pen & paper and using the TUI (PixelSense) ▪ More intense design and communication during the PixelSense stage ▪ Technical problems and delays with commercial apps ▪ Difficulties with the multidisciplinary aspect

6.1.1 Participants and Study Group Formation

The participants during the first study were design and construction professionals with experience in Architecture, Engineering and Construction (AEC) industry, including two architects (A1 and A2), a surveyor, a project manager (P.M.) and an architect/structural engineer (S.E.), as presented in Figure 6.1. The professionals had a similar range of experience of a few years post qualification and they were all PhD students at the Scott Sutherland School of Architecture and the Built Environment. The participants already knew each other for the purpose to reflect more accurately a simulation of a real-life design team with the participants knowing each other from beforehand.

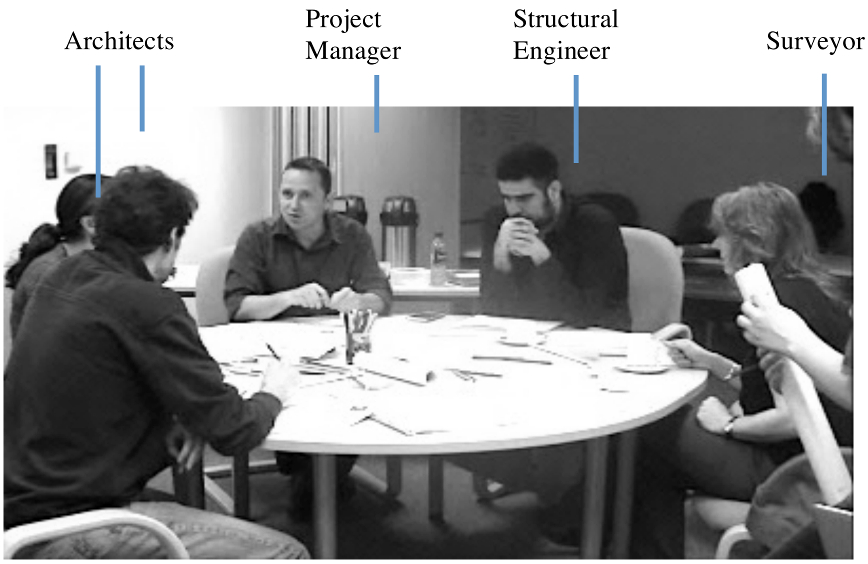


Figure 6.1 The multidisciplinary design team

The Study Group was formed following the introduction to the design task. A short presentation introduced the design problem they were asked to tackle, followed by their design investigations for providing an answer to that design problem. The implementation stage was the brainstorming process, during which their ideas were confronted from each other regarding the suitability of the proposed ideas. Eventually, the assessment of the proposed ideas was the concluding part, when the participants evaluated their own solution and gave feedback on the study to the group moderator.

6.1.2 Study's Structure and Design Mediums

The First Study was divided into three parts and two further stages within the second part, as illustrated in Figure 6.2. During the first part on the S.G. an introductory discussion intended to assist the participants to immerse within the design task they were asked to accomplish. Afterwards, an ice-breaker aimed at sharing the relevant experiences on conceptual design between the participants and making them feel comfortable within the particular context, in case they did not have previous experience on. Further details about the design brief were presented during the task explanation of the second part of the

S.G. and the actual design and brainstorming process was initiated. Certain time slots decided the duration of the process and the participants were informed both beforehand and during the process about their available time left.

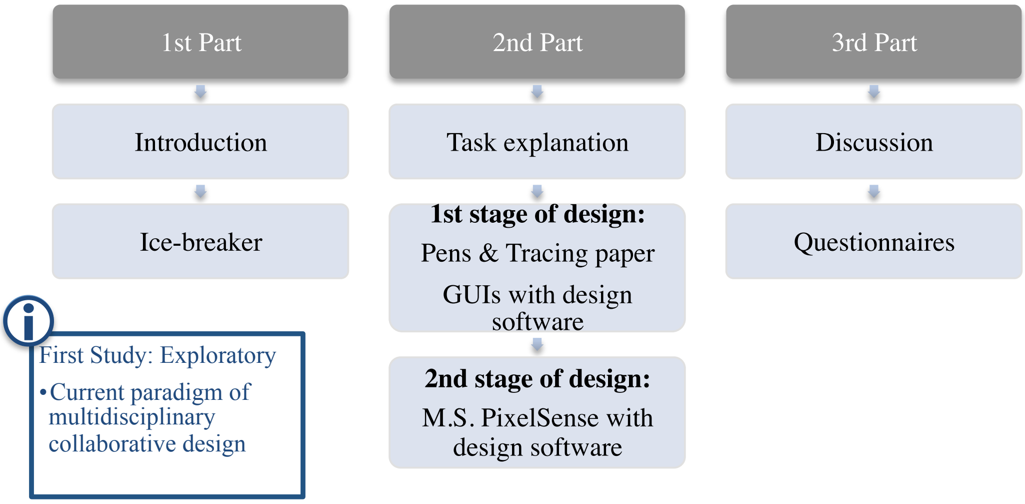


Figure 6.2 Parts and stages of the exploratory first study

The participants had a range of physical and digital tools to their disposal. The physical tools included drafting tools, drawing pencils and pens, markers with a flip-chart surface, tracing paper, printouts of the area specified in the design brief and pictures of the area. Additional tools provided for brainstorming purposes were post-its and the magnetic board with the hexagonal pieces. A range of digital media was also available for them to use, a laptop with Internet access, a desktop that assisted the moderator with the introductory presentation and the Microsoft PixelSense. The classification of the media utilised during the study are categorised in Table 6.2.

Table 6.2: Tools utilised during conceptual design

Media	**1st Stage of the Study**	**2nd Stage of the Study**
Hand-draw sketches	+	
Internet resources	+	+
Site information (pictures)	+	+
Site Drawings	+	+
Digital Sketches		+

During the second part of the study, time was divided into two separate stages and tasks, with the first one requiring from the participants to develop a conceptual design according to their choice of design mediums and the second one to continue with their conceptual ideas by utilising the Microsoft PixelSense as a design medium. The division into two stages decided the choice of the available means utilised for conceptual design; during the first stage, any type of drawing tools designers tend to use during sketching was available to the participants together with a laptop with internet connection (Figure 6.3). During the second stage of the study, the M.S. PixelSense was the proposed medium for conceptual design, with off the shelf software installed on it. The whole process lasted for two and a half hours with half an hour break, and each different part and stage of the experiment was allocated with particular time limitations.

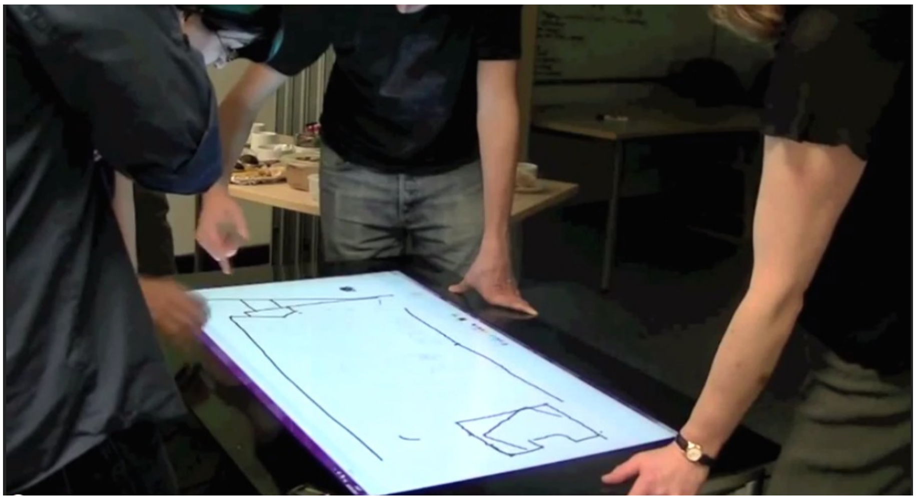


Figure 6.3 First and second stage of the study

The design tools that were available to the participants during the different design stages (analogue or digital means as illustrated in Figure 6.2) affected the end result of each stage as described in Section 6.2. The process started with a brainstorming session, with each of the participant reading the design brief, taking personal notes or drawing sketches. Afterwards, a first general discussion about shapes, materials and building' standards took place, followed by a discussion about using the space and their personal perspectives on similar types of space. During that first stage, drawings, sketches and notes were the mediums holding the information on key issues of the project like site, size and building's form. The participants utilised the provided laptop and Internet resources during both of the stages where they were searching for relevant examples of buildings, building specifications and buildings' forms. By the end of the first stage, the team did not arrive to an agreement about a potential design solution that all of the participants were approving.

During the second stage of the study, the participants continued with the conceptual design brainstorming, but this time the setting was different, which allowed a 'hands-on' experience for most of the participants by utilising the PixelSense. The participants gathered around the TUI and they had available the same type of information regarding the site and size. They also had the opportunity to merge their digital design ideas with drawing programs (AutoCAD); they experimented with it but eventually they did not use this method and software since it allowed only one user and it was difficult to use it with a tangible input. Most of the participants were comfortable with the technology and the technological barrier was intimidating for only one participant, the project manager, who still managed to provide his feedback verbally.

6.2 Results

6.2.1 Experiment and Procedure

Taking into consideration the content analysis of the verbal communication and the body language, the study initiates with the participants playing around with the stationary and making themselves comfortable in the environment. The ice-breaker effectively managed to loosen up any hesitations and they started communicating verbally and sharing their personal experiences regarding collaborative working during conceptual design stages. The personal differences, of culture and most importantly of the profession, led to different conceptions of the reasons of the study and each one of them had different expectations of the workshop.

The multidisciplinary approach of the design was also totally different compared to conceptual design meetings where usually architects are mostly participating. During the first stage of the study, the architects were leading the process followed by the project manager and afterwards the surveyor, while the engineer was participating much less. The second stage was totally different due to the use of the M.S. PixelSense, which demanded a hand-on approach from all the participants, gathering around the Table. For that particular period most of the participants were actually engaging with the drawings and all of them were more willing to participate. The design evolution of this ideation process is presented in Figure 6.4.

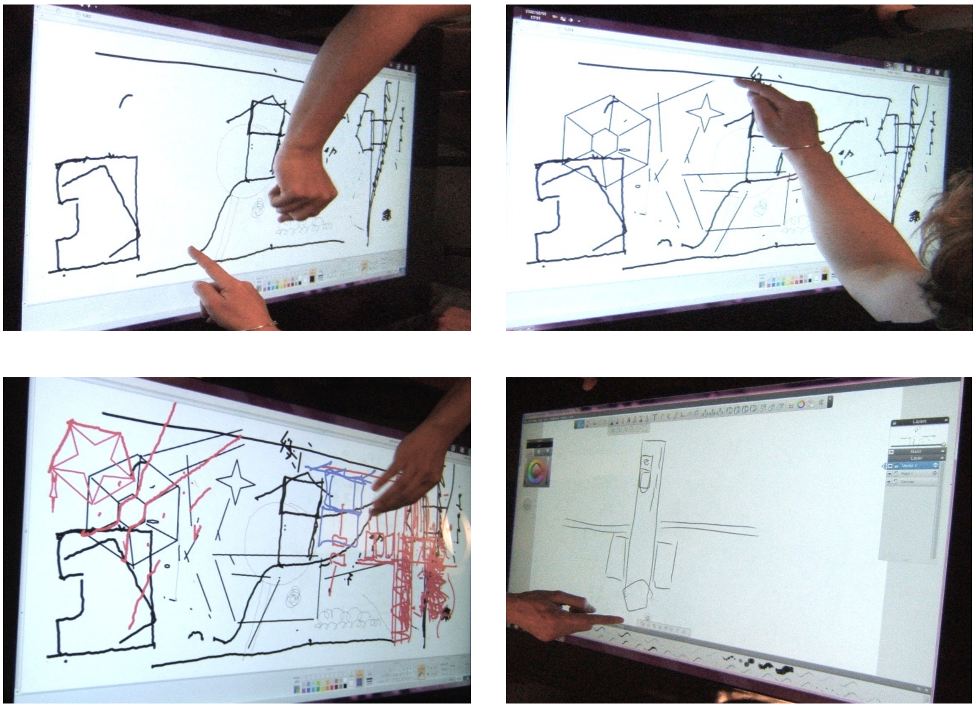


Figure 6.4 The evolution of the design ideas when using M.S. PixelSense

A semi-structured discussion took place during the third and last part of the study; the moderator led the discussion and the key findings and impressions of the participants were stated. The most important comments included, among others, the realisation from the group that the architects were leading the process and that the other participants were not usually taking part during that stage. What is more, the non-architects enjoyed ideas development and brainstorming sessions and they were happy to participate. The Internet access was also a key feature that moved the process forward by allowing access to resources, building regulations, ideas and images of other buildings and images of the site through Google maps. Regarding the problems they faced, the most important one was about the M.S. PixelSense usability and the difficulties they confronted due to the poor design of the paint application, which was not adapted for a smooth multiusers input and to the Table itself.

6.2.2 Protocol Analysis: Activities Mapping Method

The first study was focused on the current paradigm of conceptual design process; monitoring the steps of a multidisciplinary design team after a client hands in a design brief. The participants did not have any guidance and they were not provided with any walkthrough for tackling the design task. A short presentation that lasted for twenty minutes introduced them to the topic, assisted as an ice-breaker between the participants and guided them through the basic design brief details regarding the site, the building requirements and the size of the building they were asked to design. Furthermore, they were given specific time slots for completing their overall task.

The first level of analysis focuses on mapping the activities that the team followed within the duration of the study. The particular method is analysed in section 4.6. Based on that method, an activities map was created, as presented in Figure 6.5.

During the beginning of the first stage, the participants stated that usually a team would be comprised only by design relevant disciplines, i.e. architects, and not include a multidisciplinary team with quantity surveyors, structural engineers and construction managers. Each professional translated the design brief according to their profession and the initial ideas they were sharing were focused strictly on their personal perspectives. Soon after though, the ideas slowly began to bridge the different views and they were trying to reach out for their colleagues' opinions. Examples from their own experience were used to add a narrative and ease the descriptions of the different spaces. The professionals made a leap and they went straight for system synthesis, missing the system analysis and goals settings. The leap led to a series of iterations between brainstorming and analysis while the lack of particular objectives and constraints was jeopardising participants' shared understanding and consensus.

There was no particular leader within the group, and both the architects and the construction manager were driving the team, with the second one being the most experienced team member. The professional silos were still quite prominent and the less design relevant professionals were keeping a distance from the process. The overall process was moving slowly, there was a slow production of designs and no decisions were being taken for the overall project goals. The lack of particular direction led to a series of discussions on the building's typology, space organisation and energy performance. A variety of different solutions were examined and the design concepts were generally undeveloped.

During the second stage of the study the participants were asked to use the TUI for continuing their brainstorming and design activities. Ten minutes were approximately required for users to get accustomed to the TUI and learn how to use it and, as a result, the time spent on the second stage was extended. Following the introduction, the tangible interface managed to focus users around the interactive drawing surface and keep them actively engaged on communicating their ideas. They were able to discuss, design and propose possible solutions much more intensely than during the first stage and the reason being that TUI allowed for intuitive design actions.

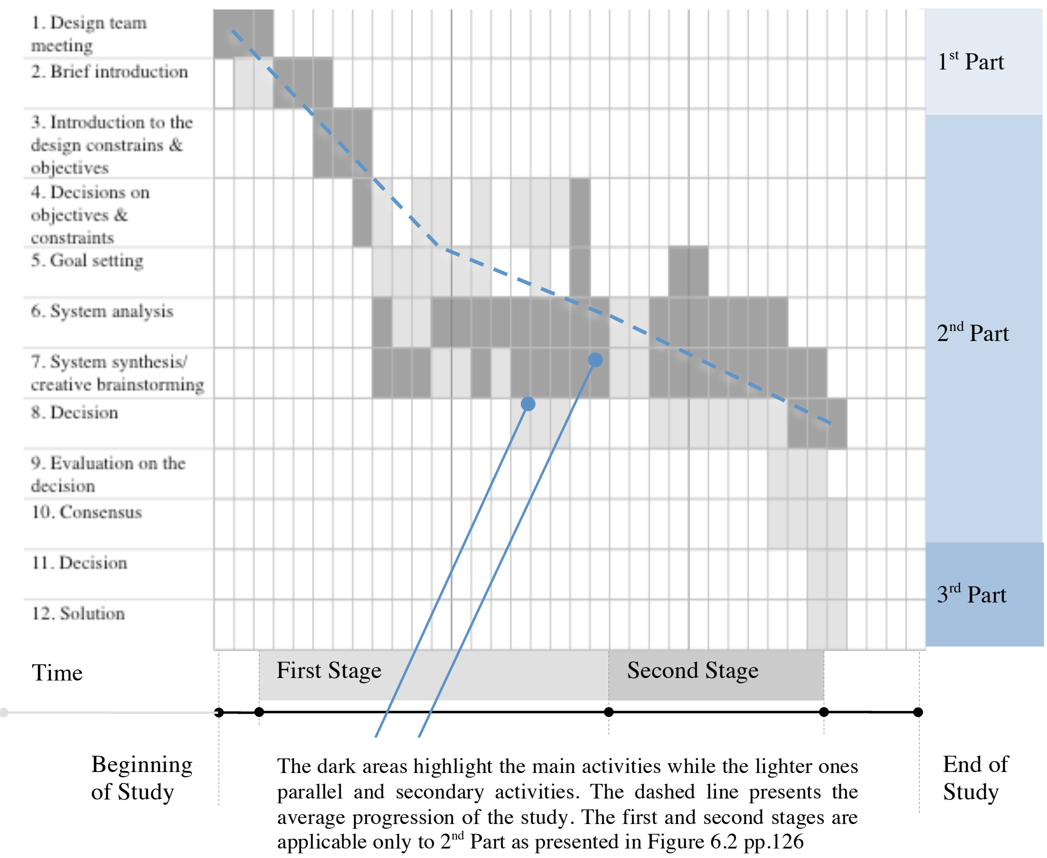


Figure 6.5 The design activity during the first study.

After the adaptation time, the professionals were able to design simultaneously on Pixelsense at a normal speed by using the drawing application and the Autodesk Sketchbook Designer; however, the system was not able to catch up with all the input.

Even though the technical problems, the professionals were able to decide on a variety of conceptual ideas and possibilities in relation to the environment, the interior spaces and the access to the building, but they did not provide a complete solution that everybody could agree on.

The team displays interdependency between the first four activities, with an in-between break, followed with more intense activities focusing on system synthesis and analysis for the greatest part of the study (Figure 6.5). The introductory part works smoothly, although the continuation with the actual design activities is fragmentary, with a great number of feedback loops between setting goals, deciding on aspects and moving back to brainstorming. The team made a leap from the introduction to the actual brainstorming without deciding on key aspects of the project during the first stage and that led to the fragmentation of the design evolution process. The participants were speculating on possible final solutions without actually deciding on a final idea. The clusters of intense activity during introduction and design were monitored and indicated with the blue lines in Figure 6.5.

6.2.3 Protocol Analysis: Actions' Coding/ 1st Study's Narrative

The second level of analysis as described in section 4.5 is providing feedback on the participants' interactions among them and with the physical and digital media, their cognitive, perceptual, conceptual and physical actions during each stage of the study according to the structure presented in Figure 6.2. The descriptions of the first study evolution are in italics and that data are analysed for providing the keywords mapping and statistical analysis in sections 6.2.4 and 6.2.5.

6.2.3.1 Actions' Coding for the First Stage of the Study

From the beginning of the study, all the participants agree on the importance of collaboration and they described examples from their personal experiences. Although they stressed out collaboration, they also highlighted that during their experience the collaboration processes were focused among same discipline groups. Most of them were working within their professional silos and their contact with stakeholders or other design disciplines was limited. Collaboration takes place during the greatest duration of the first stage.

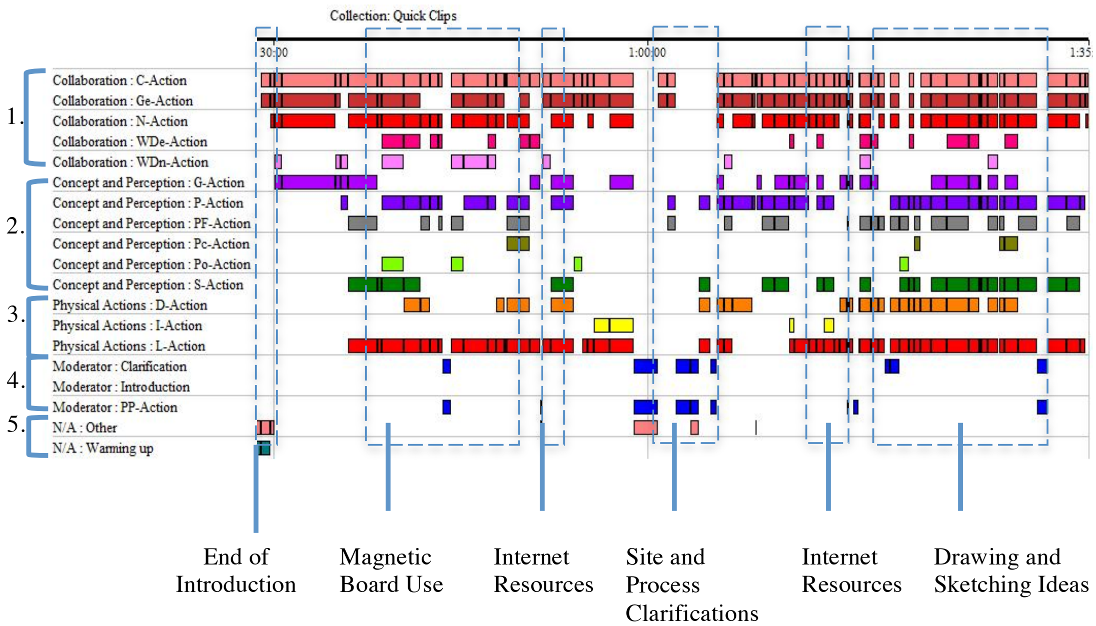
The group moderator introduced the design task and the available design mediums and digital tools to the participants. The different stages of the study were also presented to them and the overall presentation of the study is attached in Appendix D.

The conceptual design process initiated soon after a short break, until the participants felt comfortable while they were allocating around the table. Project Manager was the person who spoke first and his comment was that it was unusual for him to participate in conceptual design process. The other participants though prompt him to keep a note of "the first thing that comes to your mind". The second architect (A2) suggested to the team to consider the brief and find the aim and the objectives of the brief, the key points of their proposal, and they all agreed to follow this suggestion and keep a note of what they consider important. They started exchanging possible ideas straight after that, of things they might like the building to have and the first architect (A1) mentioned potential restrictions like the site while the structural engineer (SE) added the requirements of the brief within the list of restrictions and objectives.

They initiated using the magnetic board and during this period an intense exchange of ideas took place, with a number of different parallel actions happening at the same time. Experiments with the interconnections between different types of spaces were represented by building up connections among the hexagonal pieces. This brainstorming method allowed participants to associate and negotiate spaces and their requirements and connections, while trying to reach a solution that everybody was agreeing on. The particular process lasted for fifteen minutes approximately and it concluded with agreement on the surface of each tile on the magnetic board and with rethinking the connections between spaces. The conceptual design process continued with collaboration and exchange of ideas and negotiation among the participants regarding the best options. The first architect introduced examples of buildings from the Internet, explained how they could adapt these ideas to their own design and that led to further discussions about the adaptability of the ideas and the building site.

Additional discussions took place on modular prefabrication and the potential future expansions of the building. Participants had some questions about the site and the moderator presented briefly some pictures of the site with further explanations that led to a renewed focus on the design. The moderator was triggering the participants to contribute from their professional point of view since some of them were not willing to comment because they considered that they were involved in later and more advanced stages. This triggering led to a number of questions from the project manager to the architects and the surveyor regarding ideas on materials and on the final form of the building. The discussion continued with ideas about the site and the views of the building, while the architects were sketching potential forms. The architects and surveyor agreed on a style for the building, regarding materials and surfaces, whereas comments from the

P.M. on potential problems with the particular choice of materials kept the negotiations flowing. The participants gathered for a second time around the laptop checking resources and ideas from other buildings that led to further reflections and ideas about adapting information to their building. Following the reflection, a long period of sketching and drawing as means for ideation initiated. This resulted in a number of proposals where the participants were commenting on, regarding access to the building, numbers of floors and operational access.



Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A

The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. It is apparent in this graph that even though collaboration is almost constant it is not followed by similar intensity of conceptual, perceptual and physical activities, thus the team is mainly discussing and not evolving ideas.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. The first most intense task was drawing and sketching, followed by the use of the magnetic board. These were the tasks that the team spent the greatest time upon and where the greatest intensity of actions occurred.

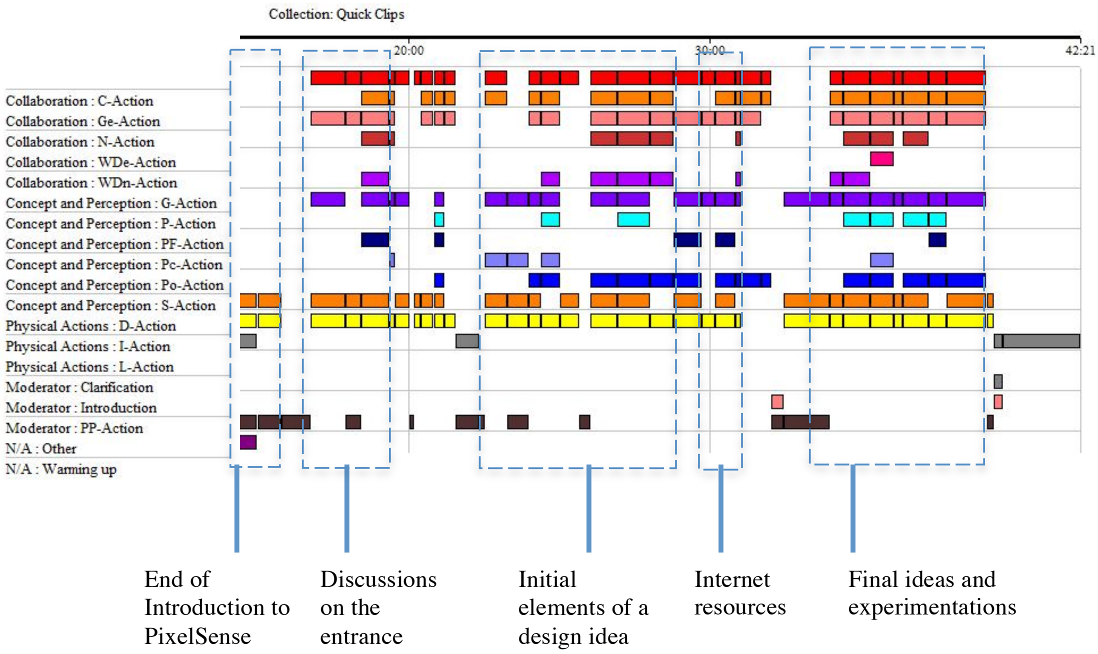
Figure 6.6 First study: first stage keyword mapping

The team continued working on different aspects of the conceptual design, with negotiations, gestures, perceptual activities and small breaks during which they worked quietly and focused on their tasks. Their ideas evolved with input on the construction and prefabrication of shells, on energy demands and on possible construction failures while the second architect stressed the importance of the design and forms too. P.M. further contributed with potential social considerations of the people who would use the building, supported by the S.E. and surveyor. More advanced decisions and negotiations about the meeting rooms followed; ideas on the creation of a terrace were also discussed by the surveyor and S.E. and the socialising spaces were further analysed from the whole team. The fist stage concluded with the team not reaching an agreement regarding which final ideas to take forward. The duration of the first stage is represented in Figure 6.6.

6.2.3.2 Actions' Coding for the Second Stage of the Study

The second stage of the study initiated with a warming up exercise that involved participants playing with the M.S. PixelSense to get used to the touch screen interactions. The moderator explained the hardware and provided them with an insight on the design software they were asked to use. The participants fairly quickly familiarised themselves with the use of the PixelSense and the design software while the moderator was providing answers to their questions. Technical problems with the technology were acting as set-backs for a smooth interaction with the means though, and that decided the software of their preference for visualising their ideas (Microsoft Paint Tool).

The team returned to the ideas they were discussing before the change of design means, thus following their conceptual design train of thought. They continued commenting on the most suitable place for an entrance to the building, with an agreement being reached between surveyor, P.M. and the second architect. The first architect drew a section for demonstrating the entrance and its relation to the site while he kept explaining on the concepts they had discussed. Further ideas on the entrance were coming to the team while they were demonstrating them through sketching on the digital media. Arguments on the topography of the area were being resolved by more intense ideas exchange through visualising and sketching them. The participants were also experimenting with the quality of different shapes and lines from the default options of the software, which additionally affected their ideation process. surveyor explained a version of her idea that included most of the aspects they had discussed for the qualities of space, while the S.E. and the first architect were analysing the space requirements. Although the team agreed on some basic aspects of their solution, arguments were still occurring regarding the shape of the building or its structure. Some of the participants were *discussing the forms on the M.S. PixelSense while other two (P.M. and A1) went back to check Internet resources and ideas. Afterwards, the participants initiated a new canvas for re-designing their final idea, with the first architect drawing and explaining their ideas on office spaces, the entrance, sitting area, with the rest of the participants agreeing on the general context of the solution. Soon after though, comments from other participants (P.M. and surveyor) raised issues on safety of the building and on other potential structural options. Eventually, the participants tried to translate their ideas into AutoCAD but technical problems on utilising it with the M.S. PixelSense restricted their design actions. The duration of the second stage with the actions occurrence during it is presented in Figure 6.7.*



Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A

The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. During that stage, collaboration was followed by simultaneous conceptual, perceptual and physical Actions, thus presenting the evolution of ideas supported by active communication and design.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. The development of the ideas occurred mostly within the duration of the particular stage and the breaks in the continuity were due to some technical problems with the digital equipment.

Figure 6.7 First study: second stage keyword mapping

Technical problems regarding the pressure levels on the M.S. PixelSense screen for inputting the design movement were quite often and the moderator was resolving these problems. During the whole duration of the second stage a very intense drawing activity was taking place, and it also allowed for a more concentrated ideas exchange for finding the optimal solution. The reason was that the M.S. PixelSense managed to focus the participants around the proposed design ideas and therefore promoted a more focused approach (Figure 6.8). Most of the participants were involved with the sketching even if their professional focus was not originally relevant with these design stages, due to the proximity of the medium and the ease of use.

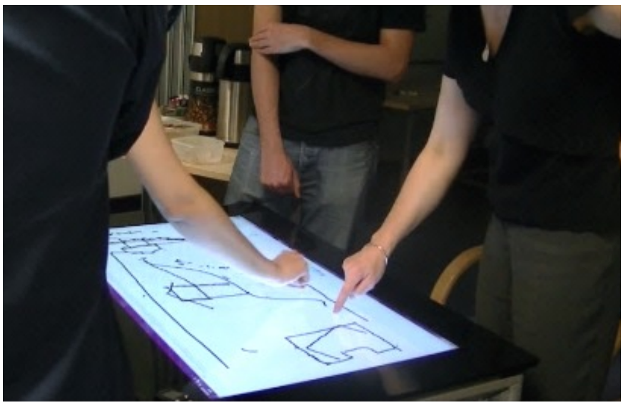


Figure 6.8 Participants focusing and working around the M.S.PixelSense

6.2.4 First Study: First and Second Stage Comparison

Collaboration was the action with the greatest duration within the first stage (70% of the first stage time: C-Action). The moderator was intervening quite regularly during the first stage to push forward the design process, provide clarifications and encourage ideation. Negotiation (N-Action), gestures (Ge-Action) and decisions on new and existing features (WDn and WDe Actions) were quite intense, with 48%, 64% and 11% duration accordingly; the perceptual activities though, for establishing a shared understanding, were quite low, which reflects on the lack of concretised decisions with the totality of the participants' agreement. Physical actions were limited during the first stage of the study too with 23% for drawing and 47% for inspecting drawings, the architects drew some sketches but they were not shared with the rest of the participants and there were no comments on them. Additional actions that took a substantial part of the study were related to warming up exercises, which were important for establishing the context of the research and the aim of the group. Further explanations on the utilised coding scheme for the purpose of understanding the different types of actions is presented in section 4.5.2, Table 4.8, page 100-101.

During the second stage of the study, collaboration related activities were not as intense as the first stage (42% duration of the second stage), but this could be explained due to the fact that collaboration was quite intense during the first stage and the key ideas were already stated. On the other hand, the conceptual and perceptual activities were slightly enhanced during the second stage, due to the greater ideas exchange with the participants focused on top of the M.S. PixelSense. That focus was also the reason for much greater physical activities, since the participants were interacting with the medium almost for the whole duration of the second stage, thus visualising and discussing their ideas. A number of technical problems though led to a greater intervention from the moderator to solve them, and these problems were interrupting and delaying the conceptual design activity. The comparison between the two stages is represented in Figure 6.9, with the percentages of duration for each activity being compared for the two different stages of the study; this figure contrasts the duration of each action as a percentage to the total duration (100%) of each stage. What is more, the figure compares the occurrence of each action for each stage regardless of the actual time they spend during each stage.

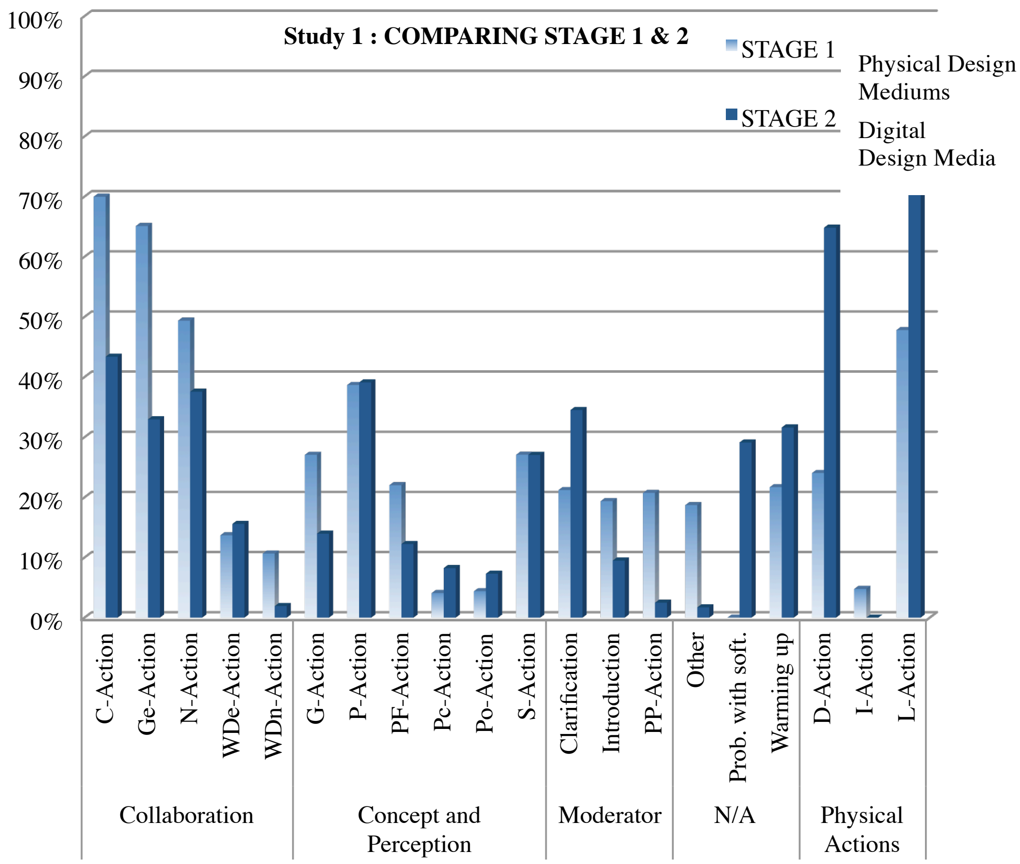


Figure 6.9 Comparing actions' duration for first and second stage of study 1

6.2.5 Duration of Segments

The participants spent two hours and seventeen minutes on stages one and two of the first Study and the protocol coding divided the Study into 131 segments (Table 6.3). The activities were parallel and shared among multiple team members with more than one action occurring during each segment, as described in Section 4.4.4 on the applied methodology. As a result, adding up the durations of the actions and the number of segments will not provide the total duration of the study or the total number of segments.

In order to understand the relation between the number of segments and the duration of each activity (raw data presented in Table 6.3) further analysis has been done that includes graphs comparing the duration of each activity with the segments' percentage from the study as presented in Figures 6.10 and 6.11. The purpose of such an analysis is to highlight that some activities may appear more often without necessarily taking longer time to complete. An additional analysis that prioritises the types of actions according to the number of segments they appear to while mentioning their duration is presented in Figure 6.12. Eventually, further clarifications on the used coding scheme are presented in section 4.5.2, Table 4.8, page 100-101.

Table 6.3 Activities summary for study 1

Actions		1st Stage of the Study		2nd Stage of the Study		Total time during the study	Total number of segments
Collaboration	C-Action	01:06:37	68	00:18:20	29	01:24:57	97
	Ge-Action	01:02:00	59	00:13:56	22	01:15:56	81
	N-Action	00:47:01	50	00:15:53	24	01:02:54	74
	WDe-Action	00:13:02	15	00:06:35	9	00:19:38	24
	WDn-Action	00:10:08	11	00:00:49	1	00:10:57	12
Concept and Perception	G-Action	00:25:46	25	00:05:54	8	00:31:40	33
	P-Action	00:36:49	41	00:16:32	23	00:53:21	64
	PF-Action	00:20:58	23	00:05:11	7	00:26:09	30
	Pc-Action	00:03:54	5	00:03:29	5	00:07:23	10
	Po-Action	00:04:11	4	00:03:05	5	00:07:16	9
	S-Action	00:25:47	25	00:11:26	16	00:37:14	41
Moderator	Clarification	00:20:11	10	00:14:35	8	00:34:47	18
	Introduction	00:18:26	3	00:04:01	2	00:22:27	5
	PP-Action	00:19:44	11	00:01:03	2	00:20:47	13
N/A	Other	00:17:48	8	00:00:43	2	00:18:31	10
	Prob. with Soft.			00:12:19	12	00:12:19	12
	Warming up	00:20:38	4	00:13:22	4	00:34:01	8
Physical Actions	D-Action	00:22:53	28	00:27:25	28	00:50:17	56
	I-Action	00:04:32	4			00:04:32	4
	L-Action	00:45:31	54	00:30:36	35	01:16:08	89
1st Study Duration and n. of segments		01:35:13	84	00:42:17	47	02:17:30	131

Figure 6.10 presents the actions of the first stage of the study and it compares two percentages for each action; the first one (blue points) is the duration of the action during that stage as a percentage to the total duration of that study stage (01:35:13). The second type of percentages (red points) represents the number of segments where this action can be found (frequency of the action) during that stage as a percentage to the total number of

segments (84) that were identified for that stage. The totality of the percentage (100%) reflects both the total duration of the study stage and the total number of segments for that stage. During the first stage, the Moderator's actions and the actions not applicable were the most prominent example of a significant difference between the percentages of the durations and the number of segments; even though the Moderator/researcher had to intervene quite often during the first stage because of the introduction and the ice-breaker, the team needed extra help to start working collaboratively. As a result, moderator's actions were occurring more often and they had short duration. This help was aiming at assisting with the details of the design brief, introducing the design mediums and providing further clarifications on the task the team had to complete. On the other hand, the Figure 6.10 reveals that the actions related to collaboration, conceptual and perceptual activities and design activities have the opposite characteristics; the duration of these actions is greater in percentage to the segments' percentage. This becomes prominent on the basis that these actions require longer time duration to evolve, i.e. the manual design motor activities need longer time to advance and the collaborative interactions require additional time to establish agreement or to complete negotiations.

Similarly to the Figure 6.10, Figure 6.11 compares two percentages for each action, the action's duration and frequency; the blue point represents the action's duration as a percentage to the duration of that stage (00:42:17) while the red point showcases the frequency of the action as a percentage of its occurrence within this stage's segments (47). During the second stage, Moderator's actions and not applicable ones are the opposite than the first stage; the interventions were lasting longer and they were concentrated in fewer segments.

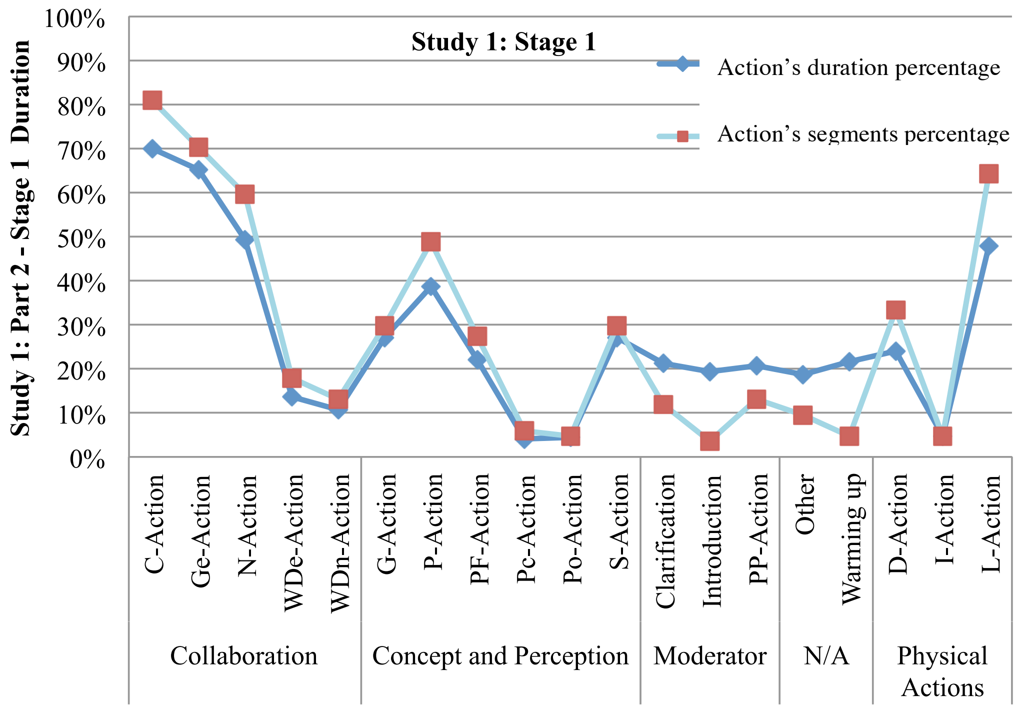


Figure 6.10 Study 1, Stage 1, comparison of percentages between actions duration and number of segments

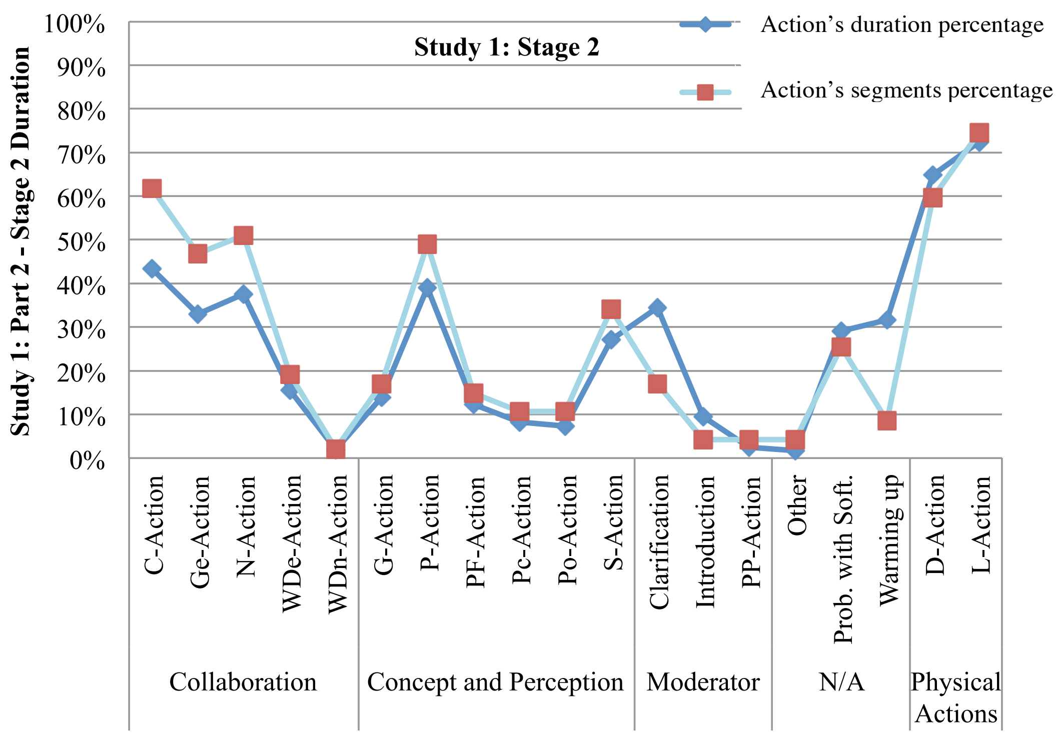


Figure 6.11 Study 1, Stage 2, comparison of percentages between actions duration and number of segments

These results were owned to the use of TUIs for continuing the conceptual design since the arising technical problems kept delaying and interrupting the design process. Because of the delays, the conceptual and perceptual activities are fragmented compared to the first stage, thus the greater number of segments and the less duration of these processes. The design activities though were not affected, since the motor actions were enhanced with the use of the TUI, resulting is quite similar percentages of duration and of number of segments.

Finally, the presentation of the actions according to the number of segments for the whole duration of the study (both stages one and two) is illustrated in Figure 6.12. The conclusions according to that presentation illustrate that collaboration was the most intense activity of the team, followed by the inspection of elements, gestures and negotiations. Interestingly, actions like focusing on different elements, designing, deciding on aspects and brainstorming are quite low, both in duration and in number of segments. As a result, the collaborative level was the most prominent during the first study, without being supported by thorough cognitive actions or design.

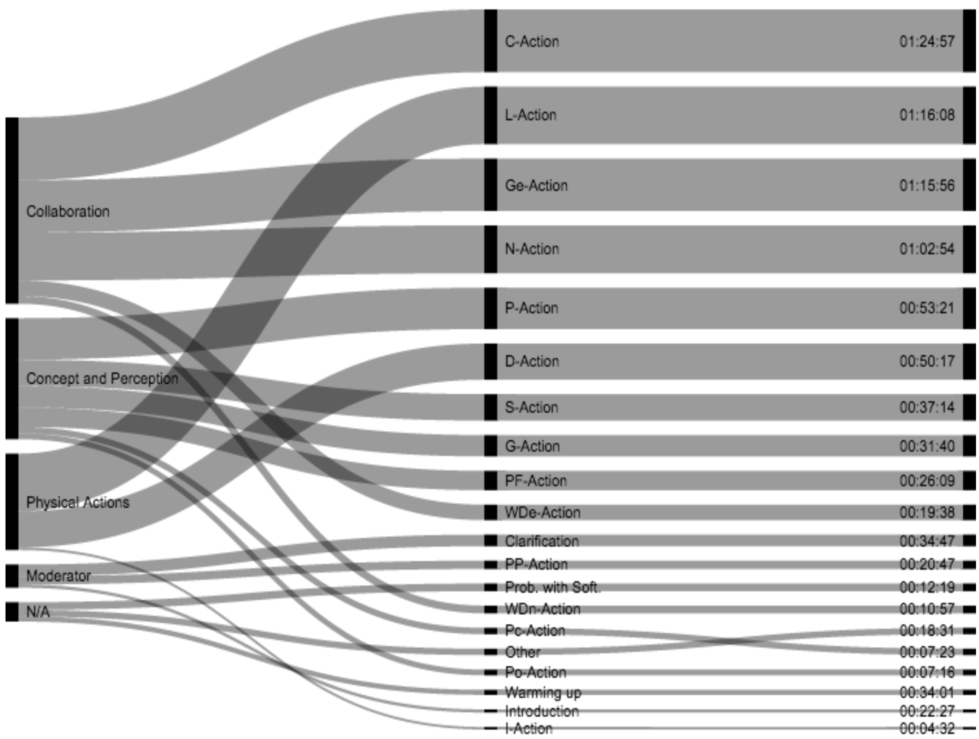


Figure 6.12 Actions categorisation according to number of segments and time during the 1st Study, for the first and the second stage

6.2.6 Questionnaires and End Discussion

After the termination of the design activity, professionals reported that they would feel more comfortable within their professional silos and they also highlighted that they would require a more complicated design brief to use their specific knowledge, i.e. budget restrictions or particular sustainability issues. The professionals also provided suggestions for the improvement of the TUI, which were considered for the development of the tailor-made application used during the second study, and they appreciated that the TUI brought them closer, allowed them to share information and have more focused discussions on specific ideas and designs.

The participants replied to questionnaires where they were asked to provide further details about any former knowledge or experience in similar design stages, feedback on the study as such and any further suggestions for improving the design process and the software. Regarding the first aspect on former knowledge, the questions were focused on their familiarity with conceptual design, with computer mediation, design mediums and means for communicating ideas. The results showcased that 80% of participants had been before in conceptual design meetings and all of them use computers at any stage of design (Figure 6.13). Furthermore, all of them tent to use computers for detailed design and less for early design and construction stages. Most of them used sketches in their professional occupations quite often; the reasons for their use of sketches were for developing ideas in a quick and easy way, for no limitations in creativity and for annotations during design evolution. The mediums that they used to implement for conceptual design were CAD programs or free-hand sketches and none of the participants had any previous experience with tabletop surfaces and TUIs for drawing or sketching (Figures 6.14-6.16).

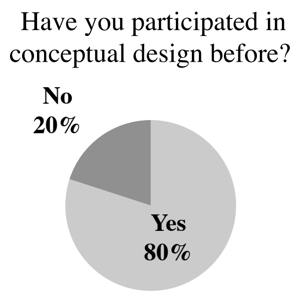


Figure 6.13 Familiarity of participants with conceptual design and computer mediation

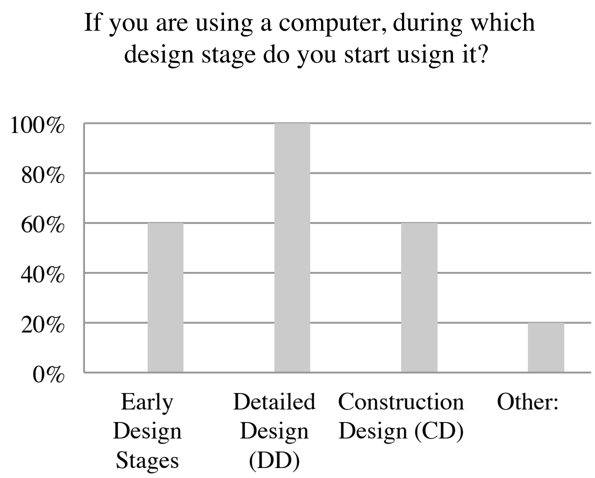


Figure 6.14 Participants' use of computers during design

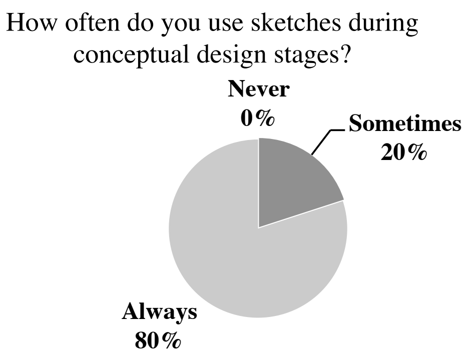


Figure 6.15 Participants' use of sketches

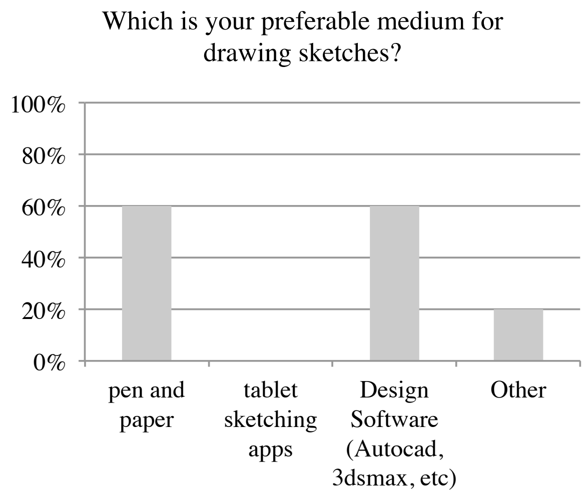


Figure 6.16 Participants' preferred design mediums

Regarding the feedback on the study, participants were pleased with the design process; they considered it productive and appreciated the different disciplines around the table since they felt it widened their vision and provided a comprehensive coverage. On the other hand though, architects expressed that they felt limited because of the technical restrictions expressed from the other disciplines and they thought that there were losing the ownership of the ideas and the control of the design. On the other hand though, when participants were asked about multidisciplinary work, they considered that the study followed quite a realistic scenario and they felt that they benefited from the different disciplines. Their personal feedback on their solution was also positive, they were happy with the design possibilities they explored regarding prefabrication, types of spaces, bridging the building to the site, topography of the site and general layout of the developed area.

Additionally, they appreciated the multidisciplinary brainstorming and found it promoted creativity. They found quite easy and straightforward to use the TUI and that fact that it brought all of them together made them more active and enhanced their focus on the solution finding process. They did acknowledge the technical difficulties with the M.S. PixelSense and they felt intimidated by the mutli-user interactions due to difficulties with inputting the lines. They also suggested further improvements, like bringing pictures from the Internet on the drawing surface and being able to use Internet while working on the drawing surface. Furthermore, they all agreed with the option to have a visual database with information relevant to the project because it would help them communicate among different disciplines.

6.3 Summary and Feedback

Regarding the aspects of multidisciplinary collaboration, it became obvious both from the literature review (Chapter 4) and from the feedback from the interviews and shadowing (Chapter 5) that the fragmentation of the AEC industry forces professionals to work in silos, with each of them employed at certain points within the design or construction process. The fact that the study gathered the key types of professionals straight from the very beginning of the process revealed the potentials of multidisciplinary working from the early design of the project, as stated and manifested from literature review and Egan Reports most importantly (Egan 1998; Egan 2008). The richness of information exchanges, the arguments' exchange and the discussions leading to new possibilities and solutions were obvious during the whole duration of the study. Additionally, the comments the participants were exchanging, i.e. "I had no idea about this", made it apparent that informed decision-making clarifies different points not considered traditionally during conceptual design.

The main disadvantage during this process was that the team did not reach any final result; they did not finish the conceptual design since they terminated the design before reaching a final solution where all of them was agreeing on. Even though the exchange of verbal ideas was vivid and intense, they did not manage to finalise a design; instead they had a collection of drawings and forms with a great technical detail. They did however exchange a great load of information and their designs were more informed and detailed. The haptic experience around a focal point (the M.S. PixelSense) moved forward the process even faster since it made them more active and engaging.

The initial pilot study also aimed at testing the capabilities of the particular TUI and off-the shelf commercial software was utilised (Drawing application and Autodesk Sketchbook Designer) for completing the design task. The feedback after the completion of the first study informed about the problems and difficulties of the commercial available software, which led to the necessity for the development of a tailor-made software, applied for the particular study and for design collaboration purposes. The problems that reported at the study were focused on the interface and the difficulties using the commands, the poor quality of lines and the drawbacks with communicating effectively the different geometric shapes. Furthermore, the participants had difficulty moving from the design activities to searching for information on the Internet and the importing of pictures from other resources was impossible. As a result, the development of a tailored application for the particular hardware that complied with certain design aspects was required for the second study.

7 Study Two

This chapter describes the findings of the second study, the application of the Conceptual Design Stages Protocol (CDSP) and of the developed computational tool for testing the feasibility and concept design stage. The first study took place among a multidisciplinary team of AEC professionals and the process included an introduction, monitoring of the steps the team was undertaking, handling questionnaires and hosting an end-discussion. Likewise, the second study follows the same structure, only this time the participants were asked to follow the process of the CDSP and to utilise a new application developed for the particular research. This study intended to test the capabilities of the proposed CDSP, its relation and application to real-life situations and the usability of the developed design application.

The first section describes the setting of the study, differences with the previous one, the components of its structure, design mediums and digital media. The second section presents the results, analysed according to different coding levels, starting with the activities' mapping, followed by actions' coding and the description of different number of segments and stages. Afterwards, the section continues with the feedback on the study, questionnaires, evaluation tool and discussion. Eventually, the chapter concludes with a brief summary of the second study that leads to the third study.

7.1 Method: Studies Components

The second study tested the developed process for conceptual design and it investigated into greater detail the interactions of participants with technology and TUIs in particular. The participants were provided with both the current paradigm of design mediums for conceptual design and with digital tools. The study followed a multidisciplinary approach and the parts that composed the second study are presented in detail in Table 7.1. Additionally, the design brief, the Moderator's presentation, the questionnaires and the evaluation tools can be found in **Appendix E.**

Table 7.1 Second study components

Design Task	▪ The conceptual design of a research hub for the Postgraduate students in the fields of design, within RGU (from fabric and fashion design to architecture, industrial design, mechanical and electrical designs, urban design). The building includes office spaces, relaxation spaces and secondary/ assisting ones.
Participants	▪ Two architects, a quantity surveyor, a building surveyor, a mechanical/electrical engineer and an architectural/structural engineer
Means	▪ Physical means (pens and tracing paper, maps' printouts, pictures, post-its, magnetic board) ▪ Digital means (laptop, desktop, M.S. PixelSense)
Method	▪ The proposed CDSP
Monitoring	▪ Two recording cameras, a digital camera, questionnaires, end-discussion and evaluation tool
Aspects to be examined	▪ Multidisciplinary work ▪ Conceptual design stages ▪ Interactions with digital means ▪ Study's design process ▪ External conditions
Critical Situations	▪ Application of the CDSP ▪ Interactions with the TUI
Anticipated outcomes	▪ Technical problems ▪ Evaluation of the CDSP ▪ Evaluation of the computational tool
Ideas for further development	▪ Shared understanding to feed into the BIM model ▪ Additional improvement of the digital platform (M.S. PixelSense)
Outputs for informing 3rd study	▪ **Further improvements for the TUI (M.S. PixelSense)** ▪ **More intense design and communication during the updated M.S. PixelSense stage** ▪ **Importing information into BIM** ▪ **Overcoming multidisciplinary difficulties**

7.1.1 Participants and Study Group Formation

The second study participants were AEC professionals, a combination of young professionals with up to 4 years experience and two senior professionals with up to 10 years experience. The team included two architects, a quantity surveyor (Q.S.), a building surveyor (B.S.), a mechanical/electrical engineer (M&E), and an architect/structural engineer (Figure 7.1). The professionals during the particular study had slightly varied levels of experience and they were comprised of PhD students and of staff members of RGU. The overall experience levels were quite similar to the first study. Some of the participants already knew each other from beforehand and a short icebreaker assisted in introducing the new participants, again simulating real-life design teams processes.

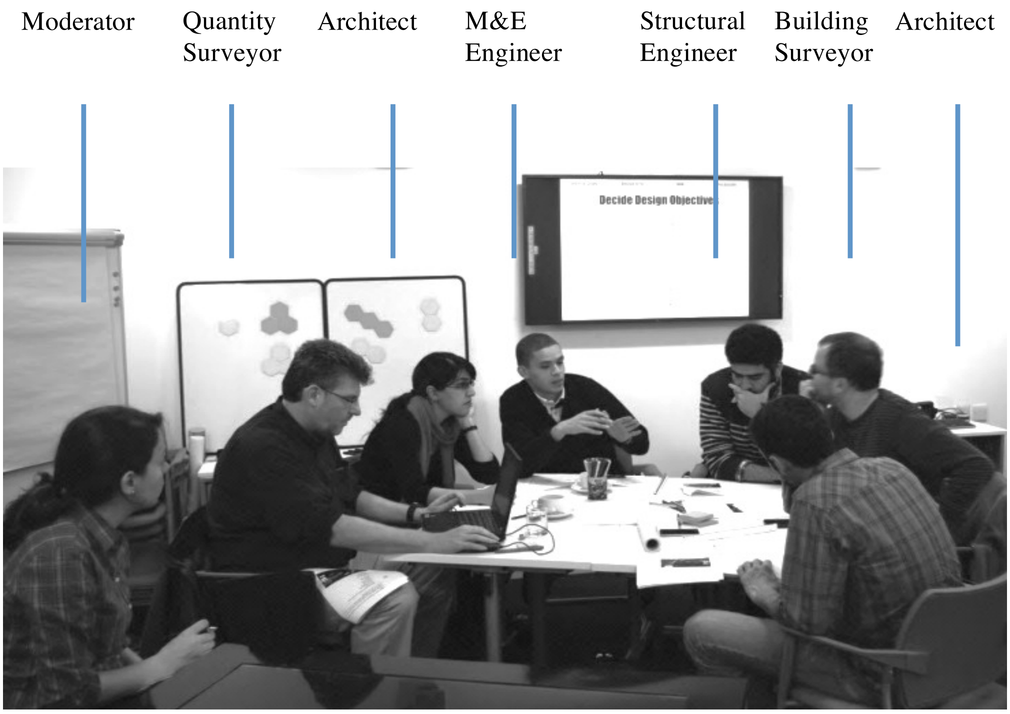


Figure 7.1 The multidisciplinary design team and the study moderator

7.1.2 Brainstorming Tools

The participants had a range of physical and digital tools at their disposal as in the first study, including drafting tools, a flip-chart surface, tracing paper, pencils, markers and printouts of the area specified in the design. Furthermore, post-its and a magnetic board with hexagonal pieces were accessible brainstorming tools. Digital media were also available, comprising of a laptop and a desktop with Internet access, a presentation screen and the TUI/M.S. PixelSense. These digital media and design mediums were utilised at different stages and parts of the study; the classification of the media are further categorised in Table 7.2.

Table 7.2 Digital media and design mediums during the 2nd and 3rd part of the second study

Digital media and design mediums	2nd Part of the study 1st Stage	2nd Stage	3rd Part of the Study
Hand-draw sketches	+		+
Internet resources	+	+	+
Site information (pictures)	+	+	+
Site Drawings	+	+	+
Digital Sketches		+	+
Inserting pictures		+	+
Integration of physical and digital		+	+
Merging with other programs		+	+

The second study had a key difference with the first one regarding the multitouch display. As it was discussed in Chapter 4, a design application (app) was developed for the particular hardware for a smoother interaction of the participants with the hardware and for taking advantage of the multitouch attributes of the PixelSense. The aim of the developed app was to enhance the augmented reality experience and achieve a natural drawing and sketching process with augmented features as add-ons, like an images library, the option to import pictures and draw on them and/or layer them and the option to pick a colour among a selection and draw with it (Figure 7.2 and Figure 7.3). The option to take notes also became available. An additionally developed option was to take snapshots of the design with the so far process and save it on the hardware, thus being able to re-use it afterwards.

The images library had a repository of pictures from similar projects, educational buildings with images of building, plans and sections (Figure 7.4). That library was developed from the moderator and its aim was to provide additional inspiration and information from similar projects for the team to utilise. Some examples of these buildings were also presented in the initial introduction from the moderator and they are included in Appendix E. Another important developed aspect was drawing and sketching on the M.S.PixelSense. The features of the paint tools were allowing users to layer their drawings, to de-activate any of them, erase lines and re-arrange their order. Similarly, the users could draw on the imported pictures and layer them (Figure 7.5). It was also important to include the option to clear the background and start a new canvas and scale and move the drawings and the pictures.

Figure 7.2 The toolbox of the developed computational design application

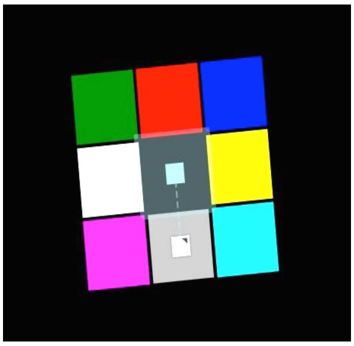


Figure 7.3 Paint tool (colour picking)

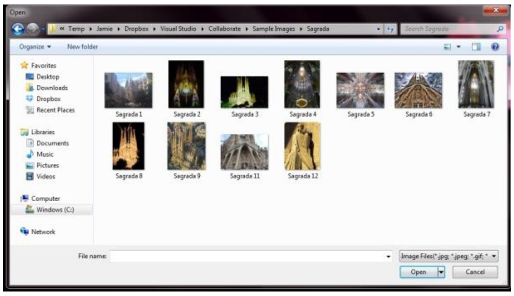


Figure 7.4 Images library

Figure 7.5 Example of drawing on top of a picture

7.1.3 Study's Structure and Design Mediums

The Second Study was divided into three parts and two further stages within the second part, as illustrated in Figure 7.6. The structure was similar to the first study up until the end of the second part. The first part included the introduction to the study group, followed by a short ice-breaker that introduced the participants. Afterwards, the explanation of the task and of the design protocol (CDSP) followed; the moderator provided instructions to the participants for the application of the design protocol throughout the study. The design brief was also introduced and similar examples of educational buildings were presented, like the plans, elevations and images of these building. The brainstorming process initiated immediately with the participants actively discussing the design problem. Similarly to the first study, the parts had a fixed duration throughout the study, which was decided by the moderator, and the participants were being informed about their time left to complete the task.

The design brief of the second study included greater detail than the first study and the reason being that the feedback from the first study suggested greater details and more realistic restrictions to the design process. As a result, the brief had the form of a project execution plan, including a strict budget, the scope of the project, a number of deliverables, the project description and design brief. Furthermore the types of different spaces that had to be included in the proposal and the regulations and British Standards that the proposal had to comply with were also part of the project execution plan. Moreover, details on the available area and the gross size of the building together with the number of people in the building were included in the brief.

The brainstorming process of the study initiated in the second part, with the use of the current means available to AEC professionals during the first stage, like sketchbooks and notepads, with printouts of the area, pictures and the detailed design brief. The participants had the option to utilise Internet resources and spreadsheets software for easier calculations through the use of a provided laptop. During the second stage, they were asked to move to the M.S. PixelSense and continue their brainstorming process by employing the developed design app for the TUI. The conceptual design process continued in the third part of the study, and it included further experimentations with the design app and discussions on the final details of the proposal. The totality of the parts and stages related to the available design means and digital media are illustrated in Figure 7.6.

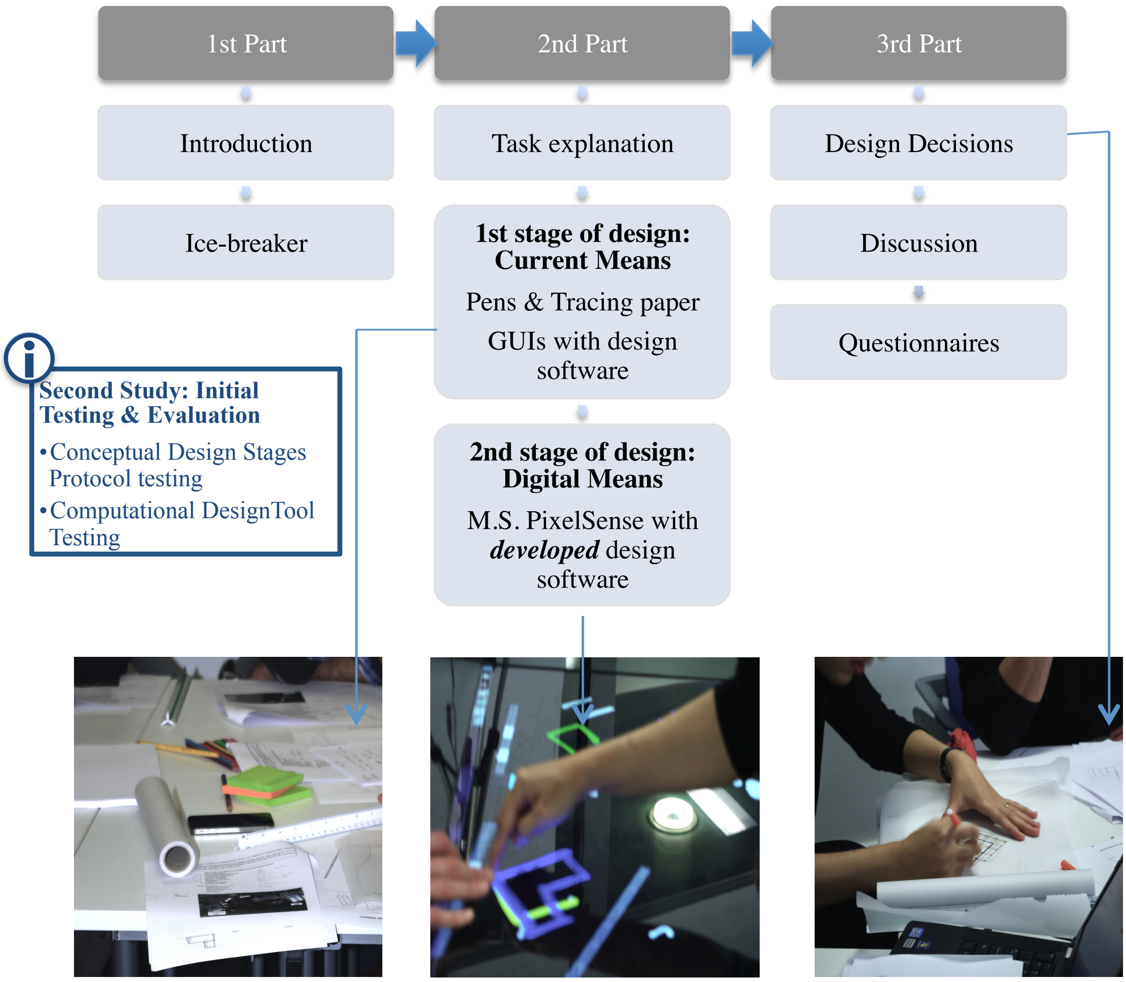


Figure 7.6 Second study's structure according to the available means and media

7.2 Results

7.2.1 Experiment and Procedure

The second study shared the same structure with the previous one, even though this time the team members were asked to utilise the conceptual design stages pre-defined protocol. The design brief this time included further information on the requirements of the project compared to the first study.

The second study tested the developed conceptual design app for the TUI, during which the use of the TUI was significantly improved compared to the first study. The physical actions during the implementation of the TUI were much smoother and the users managed to successfully integrate and merge analogue and digital means, where the participants draw in layers with tracing paper and drawings on PixelSense. The design activities were substantially more intense than the first study and, as a result, the maturity of the conceptual idea at the end was more advanced than the first study. This was mostly evident on the grounds of achieving a final conceptual design idea that responded to the objectives of the design brief. The perceptual activities were enhanced due to the more effective collaboration among the team members. The reason for that was that the TUI assisted in having them focused on the different types of relations between the building elements. The efficiency of the design app enthused the participants, thus engaging them even more actively on the conceptual design process.

7.2.2 Protocol Analysis: Activities Mapping

The first level of analysis focuses on mapping the activities that the team followed within the duration of the study. The second study's activities mapping is a method analysed in section 4.6 and its application showcased the evolution of the design process that the team followed, compared to the given predefined Conceptual Design Stages Protocol (CDSP). The purpose of this analysis was to identify if the team followed this protocol and how they adapted it to their requirements. The design process that the team actually pursued is illustrated in Figure 7.8 and the participants' feedback on the process is described in the questionnaires section of this chapter.

During the introductory first part the participating professionals had already started considering the different aspects of the building and they were asking for further details on the brief while they had already started discussing the restrictions that could potential occur, issues with the budget and the position of the building. As a result, the team was discussing the objectives and constraints straight from the beginning of the design process, thus following the pre-defined protocol. The fourth step, which was deciding on the objectives and constraints, was the most prominent for the whole duration of the first stage of the study and constant iterations were occurring between this step, goal setting, system analysis and creative brainstorming/designing. The second half of that first stage included synthesis and brainstorming while at the same time participants had to decide and finalise the proposed solution. Further details of the project, like the form, decisions on types of space, budget and its effects on the concept, were also finalised during that stage.

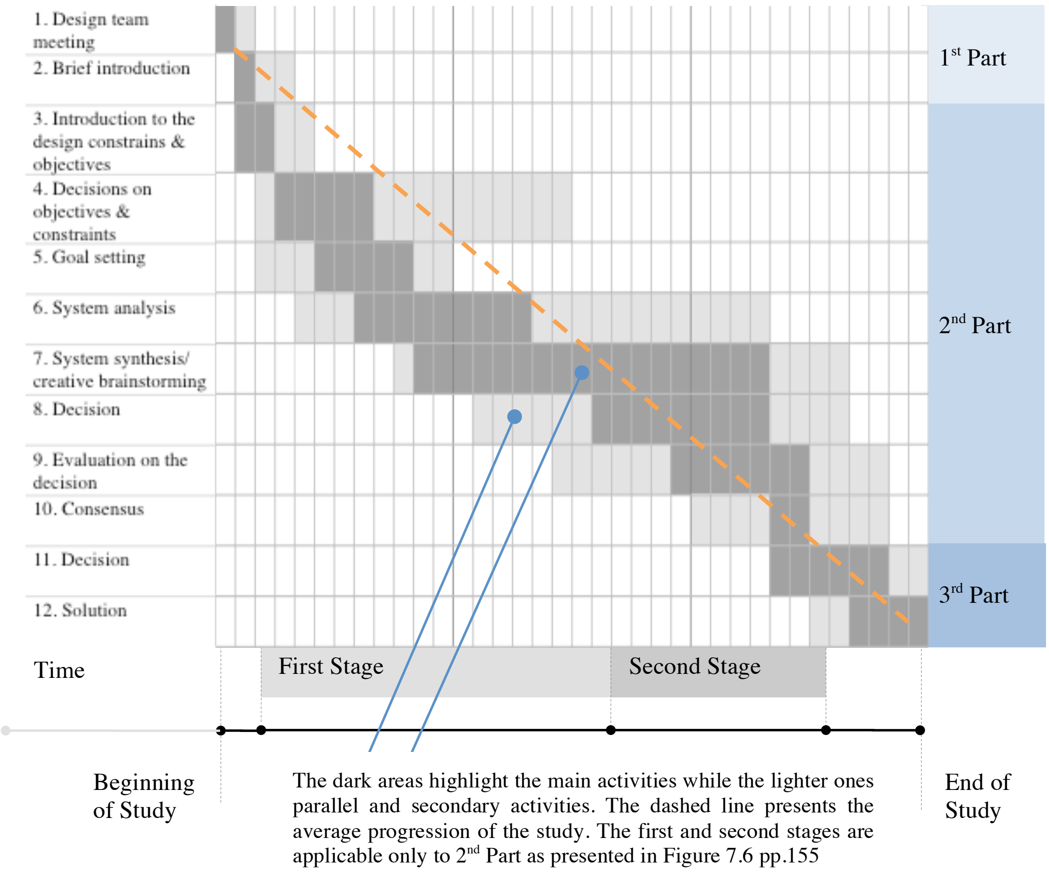


Figure 7.7 The design activity during the second study.

The professionals were asked to utilise the TUI for further design explorations, after they had finalised their goals and system's analyses, which was the second stage of the study. During that stage they continued using the pre-defined protocol and they further developed the conceptual designs. The design activities were more intense than the first stage and the maturity of the conceptual ideas evolved faster. This was mostly evident on the grounds of achieving a final conceptual design idea that responded to the aims of design question and brief. The perceptual activities were enhanced due to the more effective collaboration among the team members.

The reason for that was that during the first stage of the study the participants were situated around a table and further away from each other, making it more difficult to interact efficiently with drawings and exchange ideas on them, while during the second stage the participants were standing around the M.S. Pixelsense, allowing for a hands-on experience with the interface and the drawings, thus enhancing the physical actions by bridging digital and physical means.

The particular team included two very experienced professionals, a quantity surveyor and a building surveyor, who guided the team while still following the given protocol. Consequently, the team followed a strictly professional methodology when tackling the design problem and for completing the conceptual design. They spent significant amount of time deciding about the objectives and limitations, which resulted in a much smoother design and creative brainstorming process with less turn backs, since the agreement on objectives/constraints/aims between the professionals was achieved earlier on. During the discussions they were also reflecting on their own professional experience, they were mentioning other similar examples of buildings they had designed or they had been advisors to or similar type of buildings they had experienced themselves.

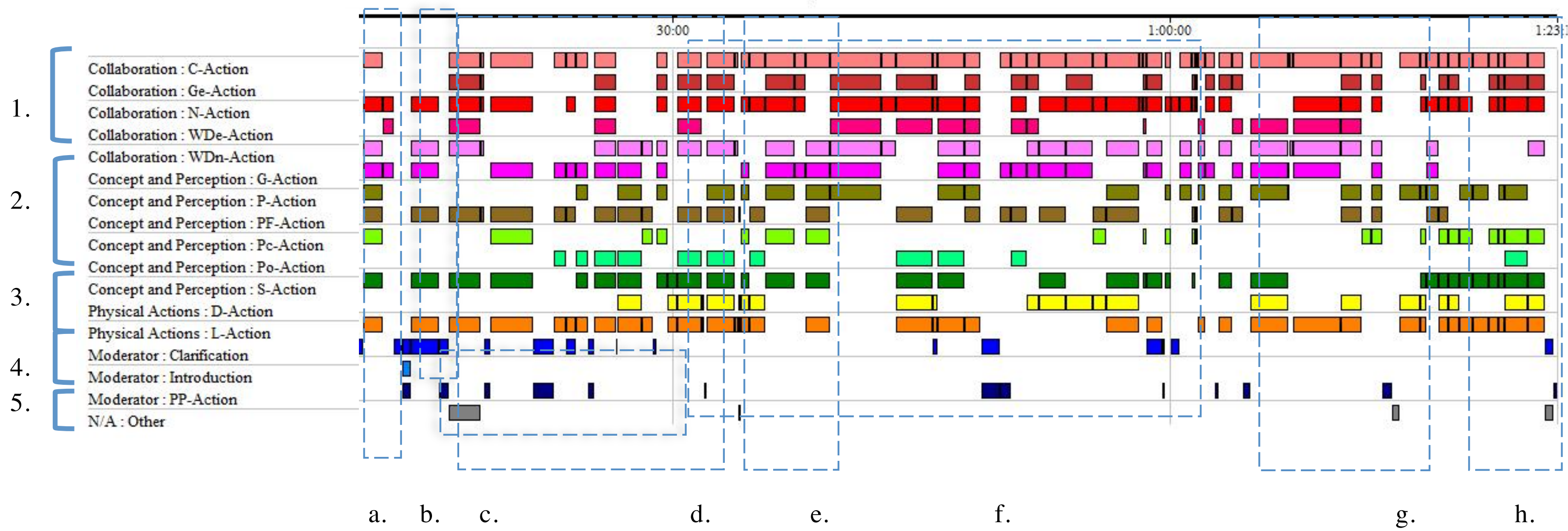
Eventually, the design followed a linear process; there was a gradual design evolution with a number of activities occurring simultaneously and small iterative steps happening during the whole duration of the study as parallel activities. This can be explained based on the fact that the design team was considering multiple options simultaneously during the design; as a result, main activities were complemented by secondary and parallel ones. There was a clear tendency to step forward by considering multiple steps at a time and focusing on one activity but still working on the adjacent ones. Such an example includes the relation between system analysis, system synthesis and decision steps, where the greatest number of iterations took place between these steps. The system synthesis during the first stage of the study was a speculative process, since the intensity of the activity was still focused on deciding on objectives, constraints and goals for the design task. Afterwards, an intensive system synthesis and analysis occurred, which lasted for half the duration of the study. At the same time, the team was evaluating the design decisions and updating them according to constraints and objectives they had set in the beginning.

7.2.3 Protocol Analysis: Actions' Coding/ 2nd Study's Narrative

The second level of analysis as described in section 4.5 is providing feedback on the participants' interactions among them and with the physical and digital media, their cognitive, perceptual, conceptual and physical actions during each stage of the study according to the structure presented in Figure 7.6. The descriptions of the second study evolution are in italics and that data are analysed for providing the keywords mapping and statistical analysis in sections 7.2.4 and 7.2.5.

7.2.3.1 Actions' Coding for the First Stage of the Study

The study initiated with an introduction from the moderator regarding the topic of the study, the multidisciplinary approach and the process that had to be followed. Additionally, the computational means and brainstorming tools that the participants were asked to use were also introduced. Afterwards, the design task, including specifications, regulations, budget of the design brief and similar examples, was presented to the team. The design group promptly commenced working on the design task and they immediately started considering restrictions and regulations that were applied to the project. The moderator was providing the necessary explanations related to the design brief, especially details on the budget and regulations that the building had to comply with. Negotiations were taking place between the professionals, and the conceptual and collaborative activities were quite intense for the greatest duration of the first stage. The participants were considering issues related to the structure and superstructure and possible problems with that from the first twenty minutes of the study; they also discussed spaces' specifications, the circulation space, the particular building type and end-users requirements. At the same time they kept notes, the quantity surveyor had already started an initial cost estimation, they kept inspecting the brief and the first architect had started some initial sketches.



a. End of Introduction

b. Design Task Initiation

c. Moderator's clarifications

d. First twenty minutes of the study

e. First instance of focused design activity

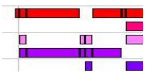
f. System analysis and synthesis initiation

g. Spaces finalisation

h. Budget's first finalisation

Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A



The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. It is apparent that collaboration is almost constant during the whole stage and it actively supported from negotiations, decisions on new elements, setting of goals gestures, brainstorming and inspecting of elements. Hence, the team is not only discussing ideas but also evolving them according to the multidisciplinary feedback.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. During the particular stage it is difficult to identify moments of intense activity since most of the duration of the stage was quite intense. The ideation process developed the project and allowed for project synthesis and analysis. Furthermore, decisions on spaces were taken according to team's consensus.

Figure 7.8 Second study: first stage keyword mapping

The second half of the hour the participants continued their task with even greater detail, stronger collaboration and clearer perceptual activities. The decisions taken during the first twenty minutes that were focusing on the types of spaces were now reconsidered. They were stating clear design problems within the specific context and they were trying to provide answers that were satisfying all the different criteria and objectives. The team was re-organising the spaces and a first cluster of design activity occurred during that part, together with a clearer idea of a cost estimation. Additionally, they were negotiating and deciding about aspects like storage space, furniture and space requirements for the different types of workshops. Technical decisions were also taken during this point, that were affecting the construction of the design brief, and the decision was focused on the number of people that could potentially use the particular building. The negotiation activities, including gestures and argumentations, and the perceptual ones, like decisions on new and previously mentioned ideas, were related to the system synthesis and analysis, and the input from the participants was constant and uninterrupted.

The last half an hour was focused on revising detailed decisions about the relation between their ideas for the design and its optimisation for cost efficiency, while *during the course of this brainstorming they were sharing understanding, taking decisions and moving forward with the design. One of the architects provided a solution for the spaces standardisation that the team further discussed, with feedback from the building surveyor regarding potential problems. After the clarifications on the topic were completed the team had a list of the different types of spaces that was given immediately to the quantity surveyor for calculations. At that point the team utilised the magnetic board for creating a diagram of the spaces with their predicted area, which was useful for the duration of the study after that point. The team reached an important point regarding the cost and the number of users with the first one increasing up to 20% while the number of users that could be facilitated increased by 60%, a result that was matching the brief specifications, which pleased the participants. Following the conclusion of all the technical details, the team concentrated on the spaces' form, they inspected the sketches of the architects and further commented and designed on top of them. The design activity was informed from the decisions that were taken up to that point and additional feedback on the building's fabric and energy consumption updated the sketches. The design was evolving with input from all the participants on various aspects and two smaller groups within the team were forming, with the first subgroup including the quantity surveyor and the first architect, and the second group involving the building surveyor, the second architect and the mechanical engineer. Eventually, the first stage of the study reached its time limit and the process stopped for a short break before the continuation of the process with the M.S. PixelSense. The duration of the first stage according to the actions' coding is also depicted in Figure 7.8.*

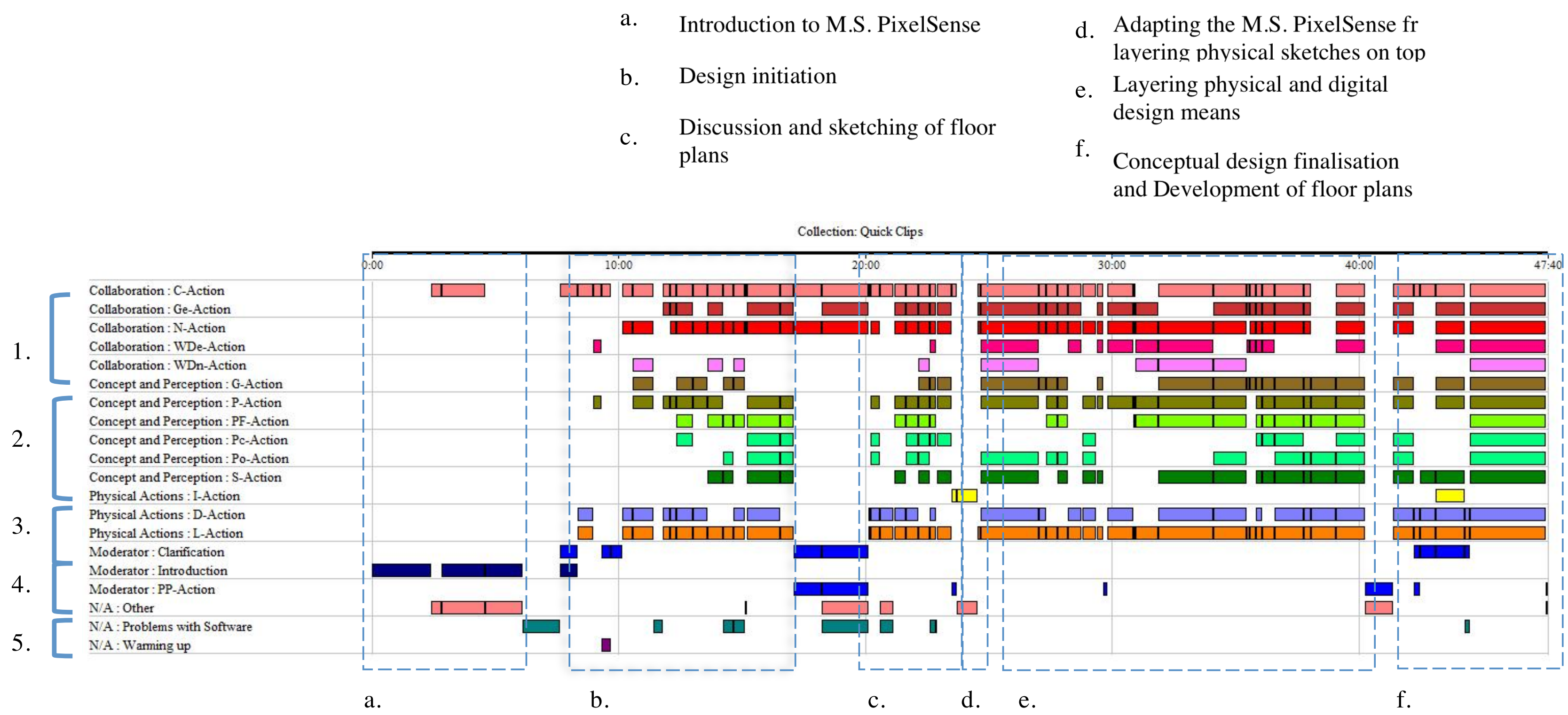
The conceptual and perceptual actions, especially of the last half hour, were supported from physical activities that involved inspecting the design brief with the specifications and sketching ideas on forms and design shapes. Negotiations were taking place within the group, not only about the conceptual design but also about the participants' roles within the team. Such an example includes a number of negotiations between the architects, the quantity surveyor and the building surveyor on the different types of spaces that were concluded with the decision to move forward with their ideas and to verify the cost after they reach an initial conceptual design; the quantity surveyor though argued against the decision claiming that some aspects should be considered from the beginning so that the cost would not increase exponentially. Furthermore, the mechanical engineer had not participated before in a similar process so it was essential to understand the context of the conceptual design and to contribute accordingly from his professional viewpoint.

7.2.3.2 Actions' Coding for the Second Stage of the Study

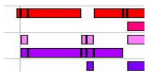
The introduction to the second stage of the study was comprised of a presentation of M.S. PixelSense, a short demonstration of the design software and some initial ideas from the participants on how to transfer their sketches on M.S. PixelSense. The moderator provided a brief explanation on how the hardware and the developed design software works and straight after the building surveyor proposed to use the layering system for transferring their sketches on the M.S. PixelSense. The participants requested from the moderator to transfer the map of the area to the interface and the building surveyor initiated the drawing activity with the rest of the participants following. They started with a basic rectangular shape that had as a consequence further comments on the size and also led them to check their hand-drawn sketches from the previous stage. Following the sketches inspection, the building surveyor continued designing on the TUI according to the input from the concurrent discussions between the architects and the quantity surveyor on building size and cost. The quantity surveyor argued on potential problems with the designed shape regarding the floor area and the building surveyor and the first architect replied to that, proposed to scale their designs and asked for help from the moderator. The drawing interface assisted them to realise additional features not considered before, like the sun path in relation to the shape of the building, potentials building shapes to optimise the benefits from sunlight and ideas on utilising an access to a nearby river and gardens.

During the brief break for transferring their drawings into scale, the team was analysing potential problems with the construction and the size of the building. Afterwards, they continued working on the design software with a relative scale of their project, a process that involved the two architects, while at the same time the building surveyor and the mechanical engineer were discussing problems of overheating of the building from the south. Plans of the different floors were slowly developing and the team discussed and negotiated the uses per floor and the types of end-users while trying to adapt to the ideas from the previous stage. At that stage, the moderator suggested them to bring their hand-drawn sketches to the TUI and compare them, an idea that was translated from the team as an opportunity to layer the physical sketches with the digital ones.

After a two minutes break to open the right type of software on the M.S.PixelSense for that purpose, the team placed the tracing paper sketches on top of the TUI. They started sketching on tracing paper, layered on top of their ideas as developed on the TUI, and the topics that they were discussing involved placing different uses within *the building, access points, storage space and potential alternatives of placing the building for avoiding extensive excavations. The team agreed that the sketches they designed represent diagrams and not the final form of the building yet. Alternative roofing systems were considered, together with different possibilities for the office spaces. They also reached an agreement regarding the number of floors for the building, a key aspect of their final solution. The design moved towards sketching the elevations of the building, a suggestion made by the building surveyor and executed by the two architects. Additionally, the quantity surveyor was informing the rest of the team the requirement for a semi-final concept for fixing the estimated cost and accordingly providing feedback, in case changes had to be made to the design. The quantity surveyor noted to the team that clearing the budget as early as possible could provide further design potentials and opportunities, a statement that the participants agreed on. The team further continued developing the sections of the building, with simultaneous feedback from all the team members; the Q.S. was adding information on the cost while the design was being developed and B.S. was further providing input on the spaces organisation, shading of the building and the superstructure. The design of the office spaces followed and all the participants approved the developed spaces, together with additional ideas on the entrance, the shape of the building and its section. The idea of building with modular systems was additionally proposed and the decision was allocated to the architects for the particular topic. A very intense process was taking place, including organising elements, brainstorming possible design solutions and deciding on various aspects accordingly. At the same time, the moderator was discreetly guiding them closer to the protocol and was also endorsing the participants to move forward with the design process.*


a. Introduction to M.S. PixelSense
b. Design initiation
c. Discussion and sketching of floor plans
d. Adapting the M.S. PixelSense fr layering physical sketches on top
e. Layering physical and digital design means
f. Conceptual design finalisation and Development of floor plans
Collection: Quick Clips
0:00
10:00
20:00
30:00
40:00
47:40
1.
2.
3.
4.
5.
Collaboration : C-Action
Collaboration : Ge-Action
Collaboration : N-Action
Collaboration : WDe-Action
Collaboration : WDn-Action
Concept and Perception : G-Action
Concept and Perception : P-Action
Concept and Perception : PF-Action
Concept and Perception : Pc-Action
Concept and Perception : Po-Action
Concept and Perception : S-Action
Physical Actions : I-Action
Physical Actions : D-Action
Physical Actions : L-Action
Moderator : Clarification
Moderator : Introduction
Moderator : PP-Action
N/A : Other
N/A : Problems with Software
N/A : Warming up
a.
b.
c.
d.
e.
f.

Levels of Action Categories:
1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A



The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. For the duration of the second stage, intense collaborative actions were followed by a similar focus on a range of conceptual and physical activities. Specifically, collaboration, gestures and negotiations were supported by a focus on different aspects of the project, sketching on the digital and hybrid media (layering tracing paper sketches on top of M.S.PixelSense drawn sketches) and brainstorming. Therefore, this stage concludes with the team's final discussions and decisions for the achievement of the design consensus.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. Similarly to the horizontal reading, it becomes apparent that this stage was of a great intensity, thus making it difficult to separate events within its duration. A close observation of the graph showcases the evolution of the design ideas, concluded with an effective finalisation of the project.

Figure 7.9 Second study: second stage keyword mapping

Subsequently, the moderator informed them about the time limitations and prompted the team to work with the digital means and finalise their conceptual ideas. Both the architects initiated working on the TUI, reproducing the sketches of the different floors' plans. The design process continued and the users were taking advantage of the diverse software design tools, like drawing with layers, erasing lines, picking lines colour and thickness and cleaning the canvas when required. The different floors layout was subjected to comments and proposals from the team; as a result, the design was adapted according to the feedback of the team. During this process, the architects and the mechanical engineer mostly engaged with sketching on the M.S. PixelSense, while the B.S. and Q.S. were monitoring the design development. The particular stage of the study was soon completed since it was reaching the end of the time slot and the moderator guided the participants back to the desk space to discuss their final ideas. The second stage of the study is presented in Figure 7.9.

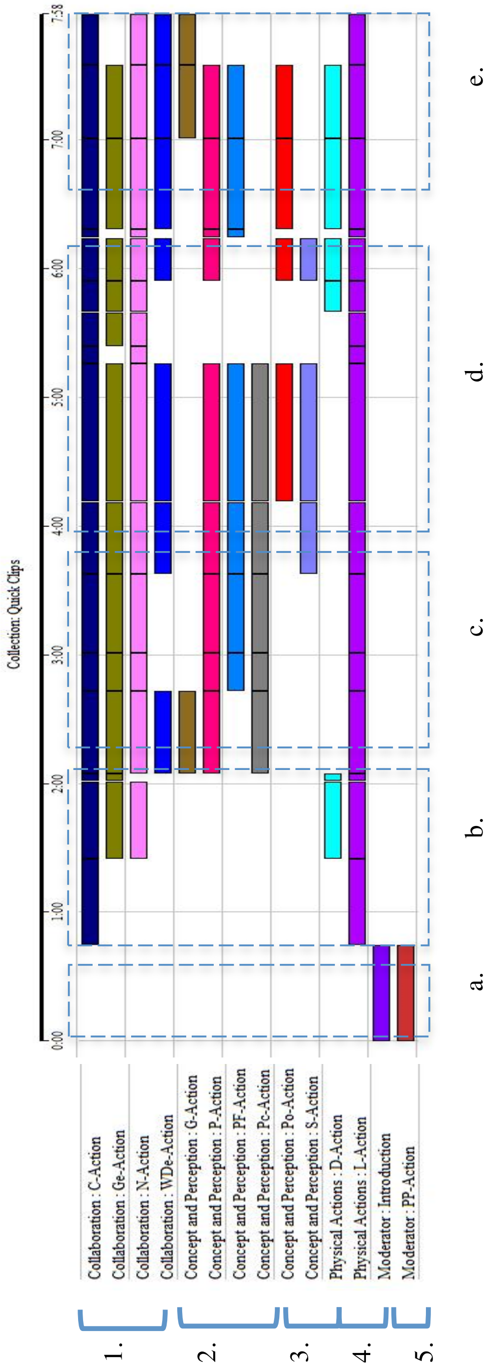
7.2.3.3 Actions' Coding for the Third Part of the Study

The third part of the study (Figure 7.10) included a short dialogue in the beginning between the team members, where they discussed their final ideas, a self-evaluation of their proposed design and a questionnaire together with a short discussion at the end. The initial dialogue was part of the conceptual design, therefore it was subsequently analysed according to the actions' coding scheme. The other aspects of the third part are analysed in the forthcoming sections.

The beginning of the third part of the study initiated with the moderator asking the team of professionals about their final idea and whether they had found one, with a positive reply from the architect and the mechanical engineer. The participants relocated to the desks, which the space where they were working during the first stage, and the discussion continued with the building surveyor inspecting the final floor plans and sections while the architects were describing it.

The discussion was focused on issues they had investigated in previous stages, like the position of the entrance, with a final agreement being achieved, and the details of the façade, with additional negotiations on the materials and the cost. Q.S. stated some further issues with the cost of the facades, and the influence on the complexity of the shapes, the ratio of the external wall to floor area, the maintenance cost, environmental impact and life cycle cost of the building. At the same time, the architects continued sketching and evolving the shape, which led to an argument regarding the particular topic; the architects wished to evolve the forms' complexity while the other professionals where pleased with the developed shapes and raised arguments regarding the cost of the building. A short description of the building and plans followed, with a further disagreement regarding the form complexity, between the architects and the Q.S. Eventually, the team worked together and developed a final set of ideas that reflected all the discussed topics with an agreement being reached at that point among all the participants. This was the point that the conceptual design was concluded with the participants commenting, "the last two hours were really productive" and the team consensus on the design was achieved. The third part is depicted in Figure 7.10.

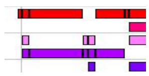
The influence of the Moderator during the study was subtle, trying to steer the discussions and guide the process when it was running out of topic or not following the process. Regarding the collaboration aspects, during the final stage of their conceptual design when the team was working on the TUI, the participants acknowledged the team *effort mentioning "this is teamwork" and also the Q.S. commented on the design "I'm even liking the design".*



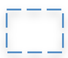
Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A

a. Relocation to the desks and third part introduction
b. Explanation of the developed ideas
c. Details on the budget
d. Argumentation regarding the budget and the building's form
e. Final conceptual design and team consensus



The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. The third part of the study is focused on the discussion of the final ideas and it is mainly a collaborative discussion and evaluation of the proposed solutions. The actions that take place during the last part include intense collaboration followed closely by focus on project's features and inspection of the developed ideas.



The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. The clusters of actions encompassed within the boxes focus on project's budget finalisation, some further negotiations and the final agreement among the participants of the project.

Figure 7.10 Second study: third part keyword mapping

7.2.4 Second Study: First and Second Stage Comparison

For the purpose of contrasting the physical mediums and digital means stages (Stage 1 and Stage 2 of Part 2 of the study), a comparison between the two of them was performed, regarding the duration percentage of each action for each stage. The entirety of activities monitored during the study was overpowering and the whole duration of the study was very intense. Furthermore, the participants followed the CDSP during the whole study.

The first stage of conceptual design included activities that were related to the identification of objectives and constraints, the adaptation of their ideas to the brief and the careful documentation of the standards and regulations they had to comply with. Additionally, the team dynamics were being established, together with the priorities of the conceptual design process. Negotiation, gestures, and decisions on new features were strong, with a great number of decisions being taken during that stage. The duration of these actions as a percentage of the total duration of this stage are 59%, 36% and 48% accordingly. Furthermore, the perceptual activities for creating a shared understanding and for brainstorming different possibilities related to the feasibility stage were equally intense, with 69% of that stage duration devoted to collaboration and 45% focused on ideas' analysis. Physical activities were also quite strong and mostly related to the inspection of different elements (52%), like the design brief, the maps of the area, and relevant information on the Internet. Clarifications on the utilised coding scheme for the purpose of understanding the different types of actions is presented in section 4.5.2, Table 4.8, page 100-101.

Collaborative and physical activities reached their peak during the second stage, followed closely by the perceptual ones, with 78% of that stage focused on collaboration, 65% on negotiations, 52% on gestures, 68% on elements' inspection and 55% on designing. The majority of the actions were increased during the second stage, with the exception of the new decisions since most of them were taken during the first stage. The digital media focused the participants around the designs, thus enhancing the exchange of ideas, arguments and solution finding progressions. The design activities were mostly prominent during that stage and the merging of digital media and physical design mediums not only increased their interest for the new design method but also affected positively the ideas visualisations. As a result, it provided a boost to creative discussions for finding a solution to the design task and reaching an agreement among the team members. The comparison between the two stages is represented in Figure 7.11. Like the previous study, the percentages of duration for each activity are compared for the two different stages of the study; this figure contrasts the duration of each action as a percentage to the total duration (100%) of each stage. What is more, the figure compares the occurrence of each action for each stage regardless of the differences in duration between the two stages.

Moderator's activities were quite low in both stages and were mostly related to providing clarifications, introducing the different design mediums, either physical or digital, and solving technical problems when arising. There was a low requirement for intervention from the moderator; the influence during the study was subtle and was focused to steering the discussions and guiding the process when it was running out of topic or not following the design protocol.

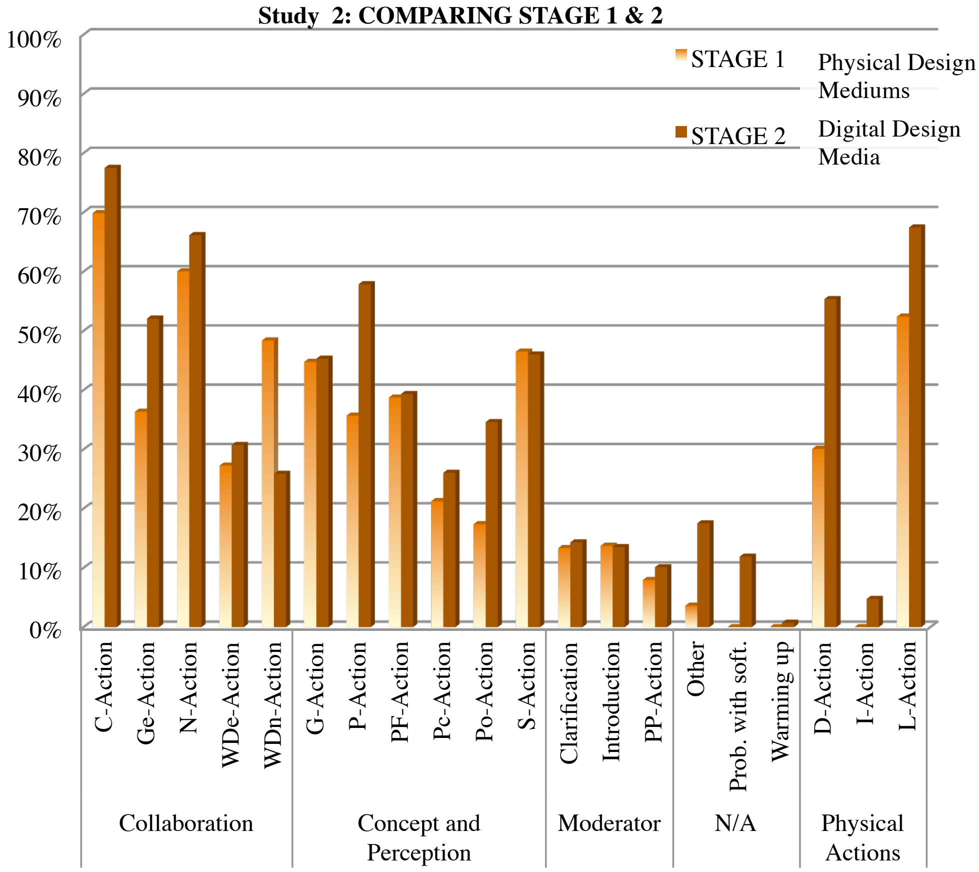


Figure 7.11 Comparing actions' duration for first and second stage of study 2

7.2.5 Duration of Segments

The participants spent two hours and ten minutes on the two stages and the beginning of the third part and the analysis was divided into 157 segments, as depicted in Table 7.3. Likewise with the first study, the activities were parallel with multiple ones occurring at the same time, i.e. brainstorming and discussing on ideas while drawing them that corresponds to simultaneous perceptual, collaborative and physical activities.

The raw data presented in Table 7.3 were further examined in graphs comparing percentages of the duration of the segments and their number within the study as illustrated in Figures 7.12 and 7.13. The intention of these graphs was to analyse the relation between these two aspects, emphasising their frequency within the study and making further conclusions on the activities. An additional analysis that prioritised the types of actions according to the number of segments they appear to, while mentioning their duration, is presented in Figure 7.14. As it was mentioned in the previous section, explanations on the actions' coding are in section 4.5.2, table 4.8, page 100-101.

Table 7.3 Activities summary for study 2

Actions		**1st Stage of the Study**		**2nd Stage of the Study**		**Total time during the study**	**Total number of segments**
Collaboration	C-Action	00:58:07	60	00:36:52	53	01:34:59	113
	Ge-Action	00:30:14	32	00:24:46	33	00:55:00	65
	N-Action	00:49:57	48	00:31:28	41	01:21:24	89
	WDe-Action	00:22:40	16	00:14:37	15	00:37:17	31
	WDn-Action	00:40:15	33	00:12:18	9	00:52:33	42
Concept and Perception	G-Action	00:37:14	34	00:21:33	26	00:58:47	60
	P-Action	00:29:41	27	00:27:32	34	00:57:13	61
	PF-Action	00:32:14	31	00:18:43	23	00:50:57	54
	Pc-Action	00:17:41	22	00:12:24	15	00:30:04	37
	Po-Action	00:14:27	11	00:16:27	17	00:30:55	28
	S-Action	00:38:40	34	00:21:53	23	01:00:34	57
Moderator	Clarification	00:11:06	20	00:06:48	9	00:17:54	29
	Introduction	00:11:25	3	00:06:26	4	00:17:50	7
	PP-Action	00:06:37	13	00:04:49	7	00:11:26	20
N/A	Other	00:03:00	4	00:08:20	9	00:11:21	13
	Prob. with Soft.			00:05:40	9	00:05:40	9
	Warming up			00:00:21	1	00:00:21	1
Physical Actions	D-Action	00:25:01	23	00:26:20	33	00:51:21	56
	I-Action			00:02:16	3	00:02:16	3
	L-Action	00:43:34	40	00:32:05	47	01:15:39	87
2nd St. Duration and n. of seg.		01:23:10	91	00:47:34	66	02:10:44	157

The analysis of the first stage is summarised in Figure 7.12. This graph compares two percentages for each action; the first one (blue points) is the duration of the action during that stage as a percentage to the total duration of that study stage (01:23:10). The second type of percentages (red points) represents the number of segments where this action can be found (frequency of the action) during that stage as a percentage to the total number of segments (91) that were identified for that stage. Within the duration of the first stage, the perceptual, physical and collaboration activities were the most prominent examples of difference between the percentages of duration and the number of segments since the team was focusing on different aspects of the design for longer periods of time. These activities were related to goals on functions, focus on and comparison of features, brainstorming actions, inspecting printed elements or online resources, sketching and keeping notes, collaboration activities relevant to decisions on new and existing features and negotiations.

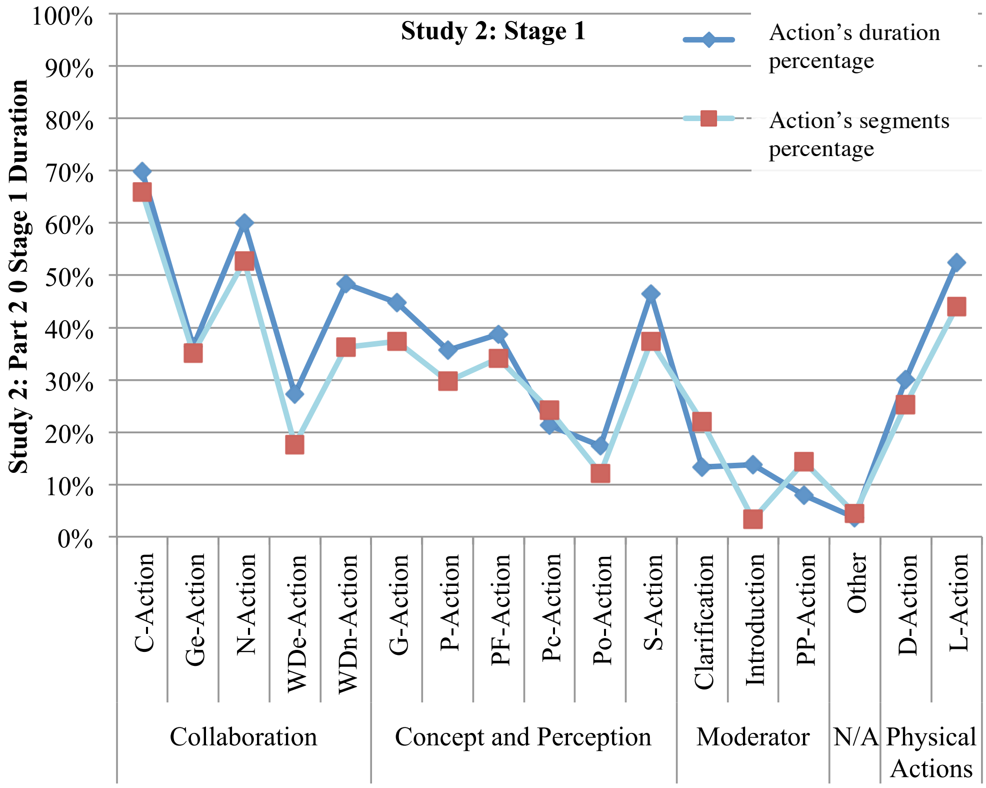


Figure 7.12 Study 2, Stage 1, Comparison of percentages between actions duration and number of segments

The introductory part from the moderator shared the same characteristics, and it lasted for a longer period of time over smaller number of segments. On the other hand, very few activities had the opposite characteristics, with shorter duration and in a greater number segments, and these ones included the moderator action for promoting the process, providing clarifications, keeping the team on track and making sure that they were following the design protocol. The reason for that was the fact that these actions had a role of providing clarifications to the team when necessary during the first stage, according to the questions asked by the participants to the moderator or in points where it was required to keep the team on track and follow the conceptual stages design protocol.

Figure 7.13 presents the analysis of the second stage of the study and it compares two percentages for each action, the action's duration and frequency; the blue point represents the action's duration as a percentage to the duration of that stage (00:47:34) while the red point showcases the frequency of the action as a percentage of its occurrence within this stage's segments (66).

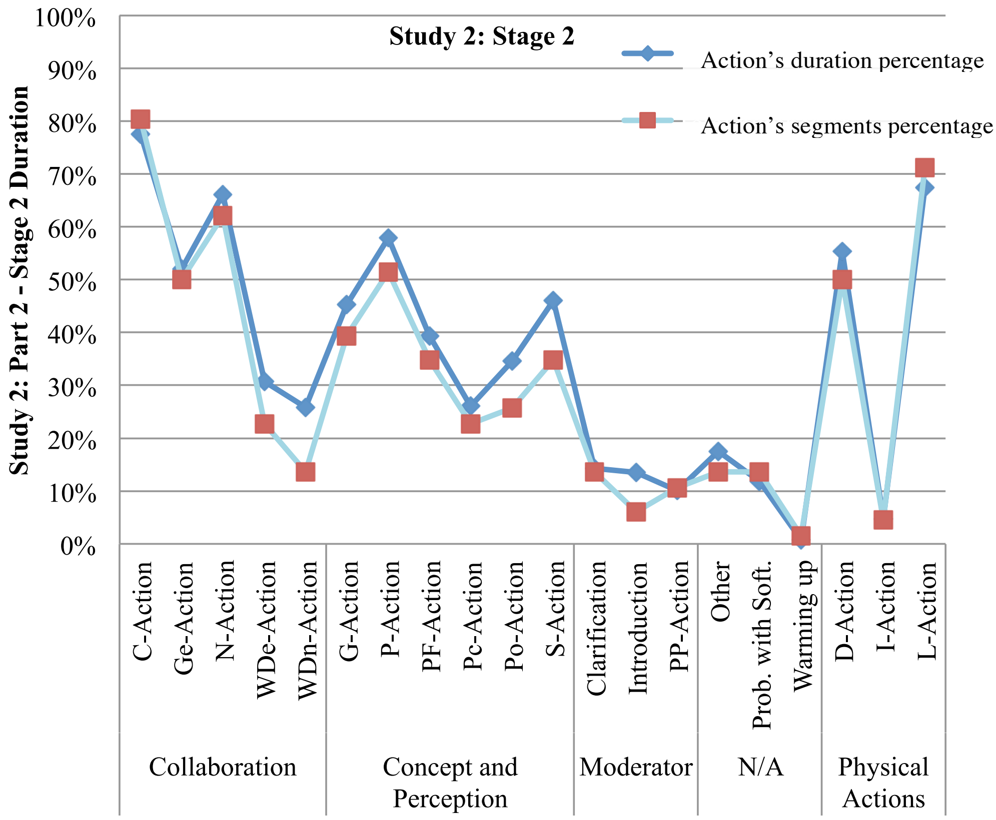


Figure 7.13 Study 2, Stage 2, Comparison of percentages between actions duration and number of segments

Throughout the duration of the second stage the majority of the activities shared the same characteristics of a longer duration, distributed in less segments. The team was focused for longer periods of time on multiple activities. The team was gathered around the M.S. PixelSense and all the actions took place around it or on top of the interactive surface. Very few delays occurred due to technical reasons and most of them were related to initiating the design software. The collaboration was even more engaging and it was assisted by thorough design activities, therefore allowing the professionals to discuss on actual sketches of the building and provide a more substantial feedback regarding the building features. The decisions were connected to the ones taken during the first stage of the study and the team was mostly focused on focusing, brainstorming, negotiating, designing and inspecting the different building features and aspects.

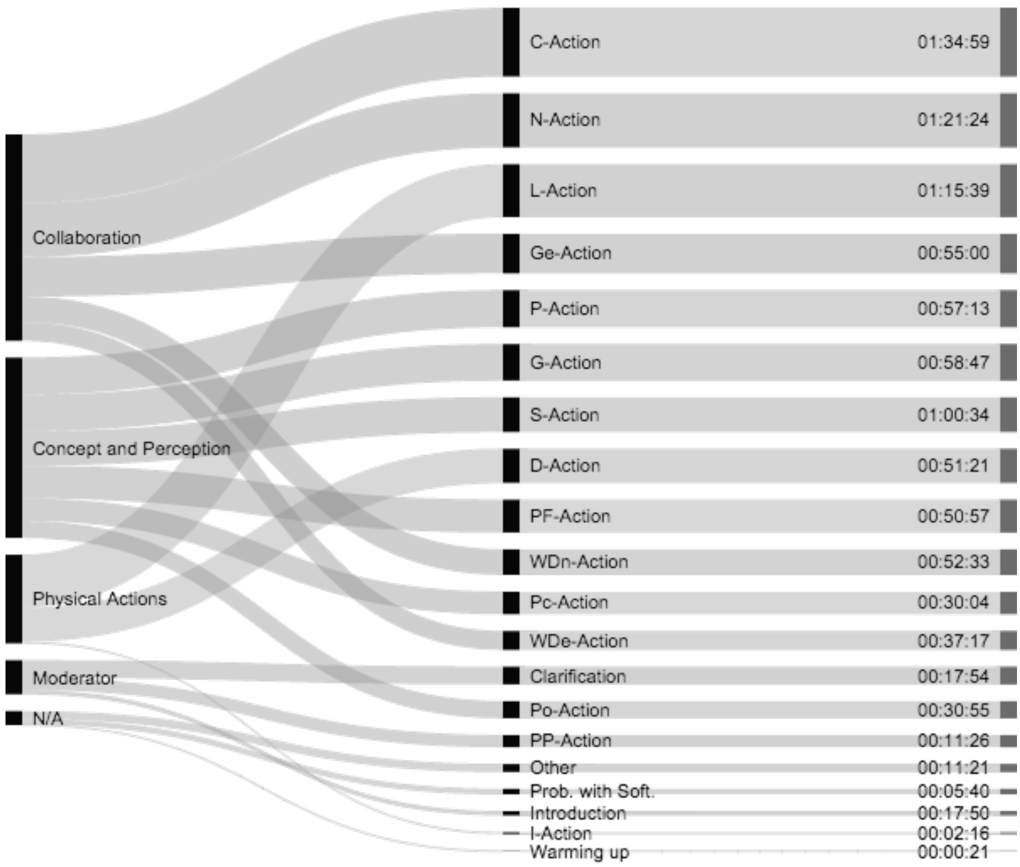


Figure 7.14 Actions' categorisation according to number of segments and time during the 2nd study, for the first and the second stage

Eventually, when analysing the whole duration of the study according to the number of segments as illustrated in Figure 7.14 a number of conclusions can be drawn. To begin with, collaboration, the action of inspecting the different elements, negotiations and gestures were included in most of the segments of the study, followed by focus on elements and ideas, setting goals for new and existing functions, importing pictures and designing. Interestingly though, collaboration, inspecting elements and negotiations had a quite similar duration, of an hour and a half, while the actions of importing pictures and drawing even though they were observed in the same number of segments, the first one lasted for three minutes while the second one for almost an hour. As a result, some actions were most prominent for longer duration in fewer intervals, like drawing, problems finding, decisions on new and existing features and brainstorming, while others were detected in larger number of segments but with less duration, like warming up, importing pictures and facing problems with the software.

7.2.6 Self-Evaluation Tool

The third part of the study started with the finalisation of the conceptual design, which was part of the design protocol and the brainstorming process, while afterwards a self-evaluation tool was distributed to the participants to rate their ideas, followed by a questionnaire and a short end-discussion. The self-evaluation tool, which was based on design quality indicators as described in Section 4.3.5, was utilised for assessing their end result according to three aspects, impact, built quality and functionality. The tool intended to provide feedback on the design solution with its strengths and weaknesses coming from the involved parties, the team of professionals. Eventually, it targeted to discover whether the process was successful from the participants' viewpoint.

The team was overall pleased with the conceptual design and the details of the feasibility stage that they produced during the study, as it is illustrated in Figure 7.15 and Figure 7.16. The most successful aspects of their outcome were related to the use of the project and the quality of spaces, followed by character and innovation of the building, form and materials, internal environment, urban and social integration and access (Figure 7.15). Performance and construction had an average good value and the lower value was given to engineering systems. The evaluation reflected their process and the focus of their ideas during the study, the key topics they discussed for longer duration and also the fact that the multidisciplinary approach provided a holistic view of the project and achieved an integrated project delivery, since most of the aspects had a good grading (Figure 7.15).

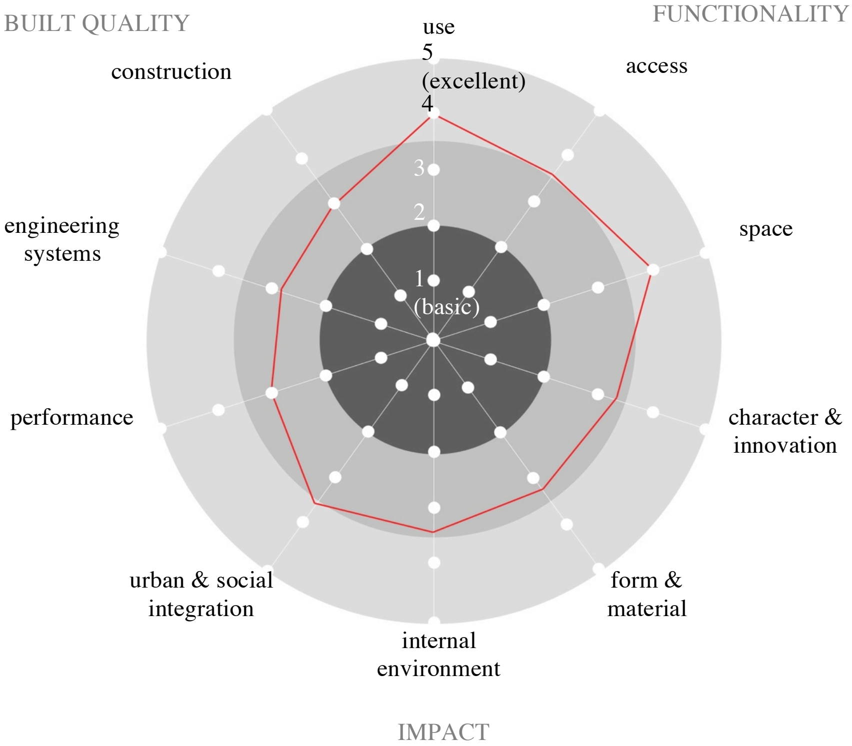


Figure 7.15 Self-evaluation tool, average responses

Considering the graph that represents the individual evaluations (Figure 7.16), it is evident that some participants followed a more conservative approach when rating their ideas, thus being stricter with the grading, while others were more generous when grading the different aspects of their design solution. The strictest evaluation came from the quantity surveyor, who considered that the greatest emphasis of their solution was focused on character and innovation and the quality of spaces, while the poorest performance was located in construction, integration and performance of the building. On the other hand, the most optimistic evaluations came from the architects and the building surveyor that considered the most successful aspects to be the use, the access and quality of spaces and the lower grading was given to engineering systems and building integration.

The participants were in agreement when rating some of the characteristics of their solution, with smaller deviation observed in internal environment, forms and materials, use, and quality of spaces. Figure 7.16 presents the collected data and the different colours showcase the different replies to the evaluation tool. For the purposes of this research it was not required to identify the different professionals providing the answers, therefore Figure 7.16 showcases the raw data that were further analysed in Figure 7.17 according to their deviation.

A much greater deviation was monitored when evaluating aspects like character and innovation of the project, access and performance. The reasons for that can be located in their discussions afterwards that identified their perceptions of the process; they believed that not enough time was spent on topics of their professional focus. The quantity surveyor considered that the form and character of the building was analysed in greater detail than the construction or performance, while the first architect was not happy with the character of the building and considered that performance and construction were analysed in detail. Interestingly, the rest of the participants provided similar grading even though their different professional background and the detailed design quality indicator with the individual responses is presented in Figure 7.16.

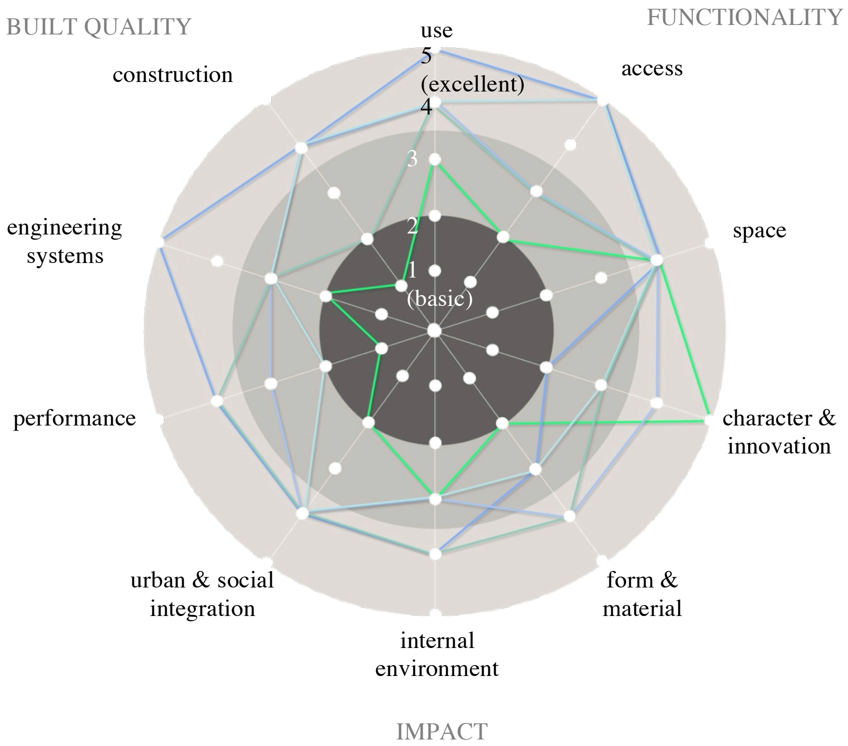


Figure 7.16 Self-evaluation tool, individual responses (each colour represents one participant)

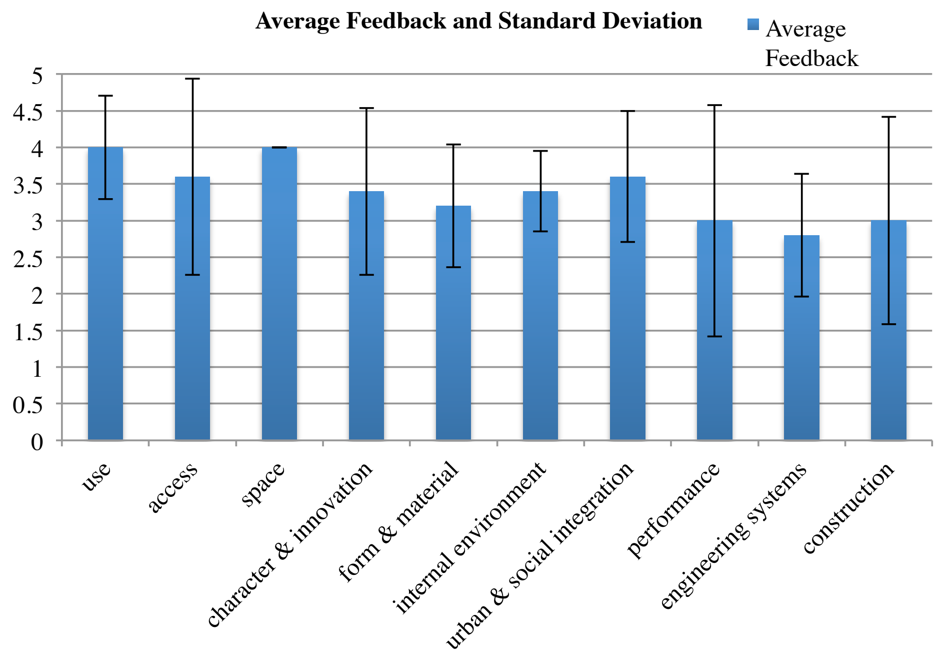


Figure 7.17 Self evaluation tool, average responses and standard deviation for the 2nd study

7.2.7 Questionnaires and End Discussion

Questionnaires' distribution followed the evaluation tools feedback. Like the first study, the questionnaires initiated with a first section for monitoring former knowledge of the participating professionals and their familiarity with processes, digital media and design means. The first aspect to be examined was previous experience in conceptual design, will all the participants having practised previously, with the exception of the mechanical engineer (Figure 7.18). The use of computers during design was also inspected, again with the majority always using computational tools and one professional using them frequently (Figure 7.19). All of the participants answered that they start using a computer during the early design stages, and most of them replied that they always use sketches during conceptual design (Figure 7.20), due to the flexibility it provides, the brainstorming ideation for developing ideas, concepts and forms. They also explained that they tend to recognise their initial ideas to the developed drawings frequently, and less often always and sometimes (Figure 7.21). Their preferred design mediums for drawing sketches were pen and paper and less often design software (Figure 7.22) with all of them keeping notes during the process of conceptual design.

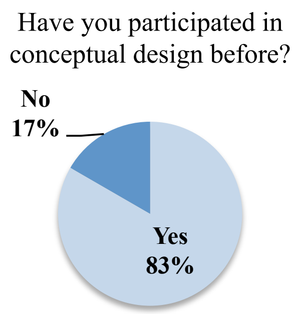


Figure 7.18 Previous experience related to conceptual design

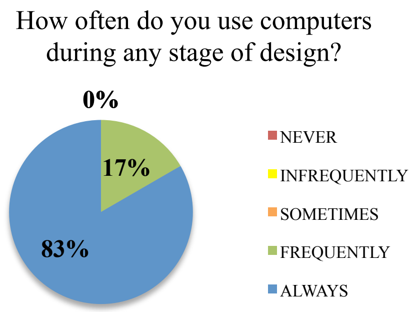


Figure 7.19 Frequency of computers' use

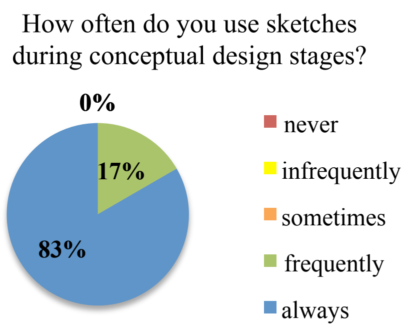


Figure 7.20 Frequency of use of sketches for concept design

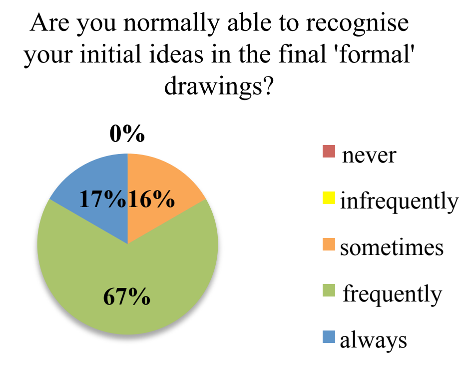


Figure 7.21 Ideas' recognition in final design

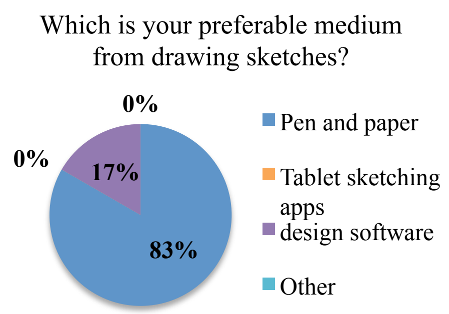


Figure 7.22 Preferred design medium

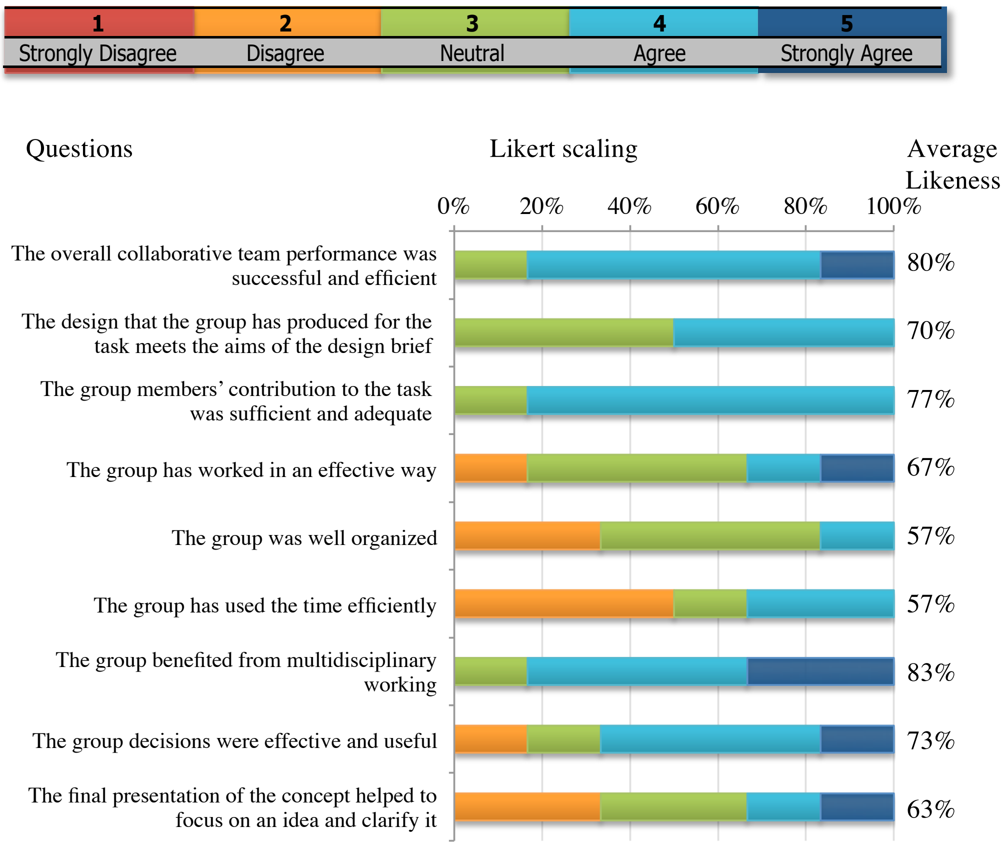
During the second section of the questionnaires, a Likert scale was employed for the study feedback, since it was the most suitable tool to provide the self-reported users' perception (Tullis, Albert 2013). The particular system was able to capture the experience of the participants and their personal opinion. A classic type of scale was utilised as depicted in Figure 7.23 with a five-point scale of agreement, ranging form strongly disagree up to strongly agree. It was also essential to form the statements of the questionnaire in such a way that they did not evoke potentially different attitudes than what expected, meaning that strong adverbs suggesting extreme likeness or dislikes were not used, i.e. words like very, totally, extremely. Three different categories of Likert questionnaires were also implemented, testing the overall and group feedback, the effectiveness of intended use of the conceptual design protocol and the user satisfaction and application (design software) efficiency.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Figure 7.23 Likert scale

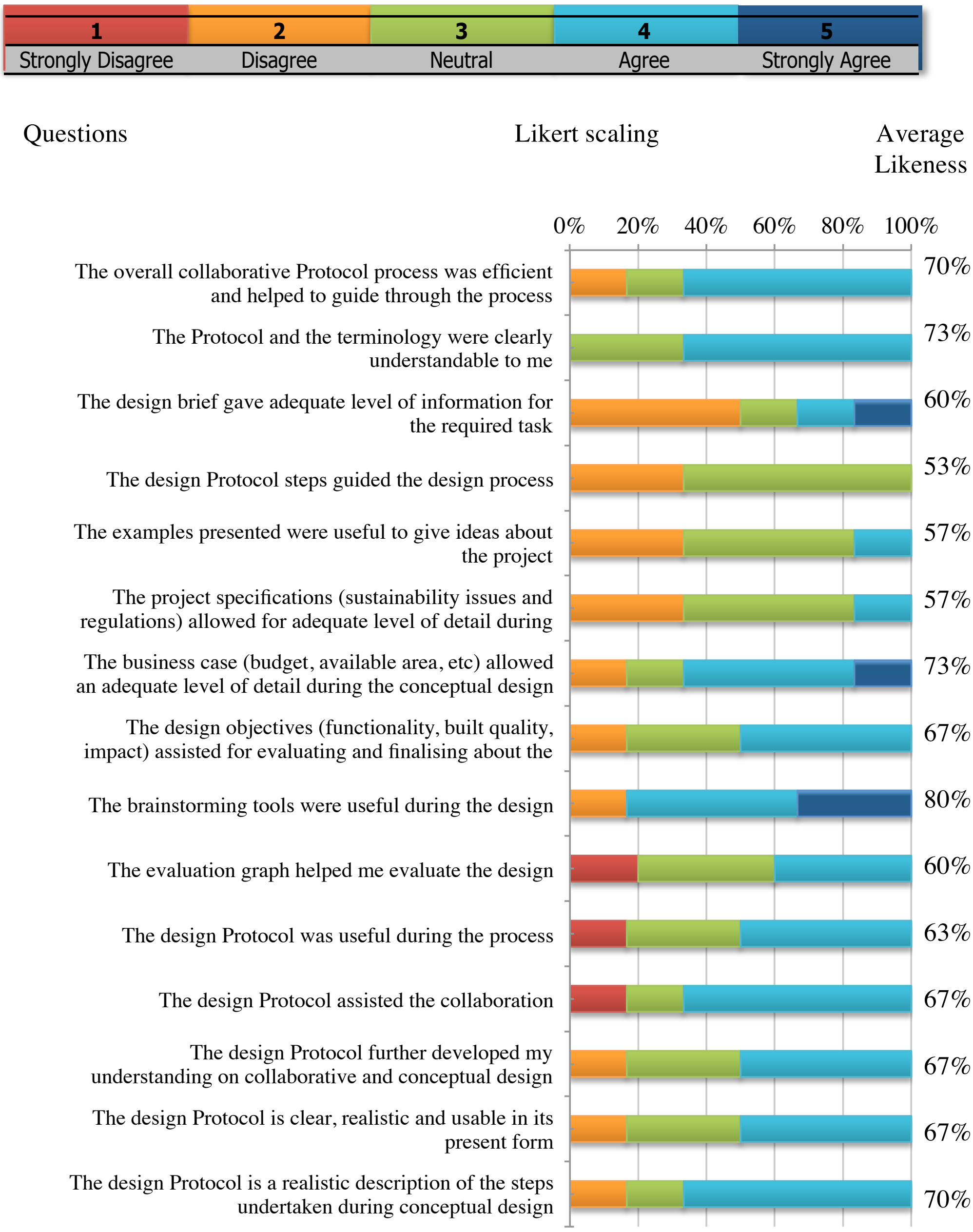
The first category of the second section of the questionnaires planned to provide feedback on the overall process related to the group work and the multidisciplinary working (Table 7.4). The participants were overall pleased with the process, since all the replies were above the neutral margin. The greatest number of positive replies came from their agreement that the group members' contribution was sufficient and adequate, their perception that the collaborative team performance was successful and efficient and from the realisation that the group benefited from multidisciplinary working. They also agreed that the end solution was meeting the design brief requirements. In addition to this, more neutral-positive replies came from aspects like effective overall group-work, good organisation within the team and satisfaction with the final solution presentation regarding the concept.

Table 7.4 Overall and group feedback Likert scale replies



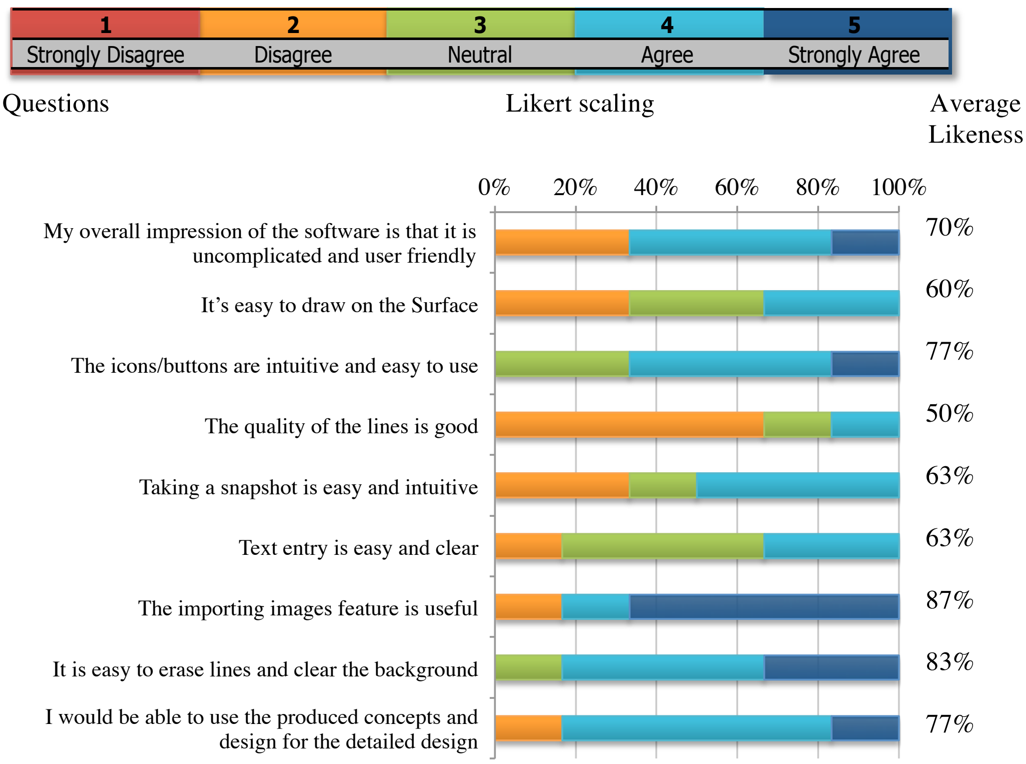
The second part of the questionnaire provided input with a focus on the process followed during the study and the use of the predefined conceptual design protocol (Table 7.5). This time, the average feedback was less strong that the first part of the questionnaire, but still provided valuable information for the Protocol employment during the study. The participants were overall happy with particular aspects of it, they believed it helped them through the process and it was understandable. Additionally, it assisted collaboration and further developed their understanding on collaborative and concept design. Eventually, they believed that the protocol was a realistic description of steps taken during concept design. They were pleased with aspects like the details of the design brief, the design objectives, brainstorming tools and the usefulness and clarity of information provided by the Conceptual Design Stages Protocol. Neutral input derived from further aspects, including the adequacy of information included in the design brief, the existence of relevant building examples, the detail of project specifications and the evaluation graph.

Table 7.5 Effectiveness of intended use of the Protocol Likert scale replies



The third part of the questionnaire was concentrating on the user satisfaction from the use of the developed design application for the M.S. PixelSense. The feedback was overall good and the participants believed that it was uncomplicated and user friendly, with especially positive input regarding the features of importing pictures, the ease to erase lines and the intuitiveness of the buttons. A neutral/positive impression was coming from aspects like ease of drawing, quality of lines, ease of taking a snapshot and text entry. Finally, they perceived the design application as a useful mean for producing conceptual designs to be used for detailed design. Regarding the overall responses on the M.S. PixelSense application, the aspects that had to be further improved for the third study included the quality of lines, the intuitiveness of designing on top of it and of using the toolbox, and the ease of layering the drawings.

Table 7.6 User satisfaction and application efficiency Likert scale replies



An end discussion succeeded the completion of questionnaires, during which team members reported that the design protocol would still have to tackle differences between different types of professionals and that it would have to be adapted for a longer period of time. They were pleased with the quality of solution they had by the end even though they did not achieve to consider significantly some aspects of the proposed concept, like the engineering systems, details on the form and the character of the proposed solution. They still managed to tackle issues like use of the building, access, types of space, construction, performance, urban and social integration and basic ideas on forms. Most of the professionals realised that the time constraints put pressure on the process and they were feeling that they could contribute more to the solution if they had more time.

The multidisciplinary aspect was also clear from the beginning; the participants formed quickly a strong team and all of them contributed to the process. The quantity surveyor undertook the cost estimations and mostly the architects focused on the design, but the collaboration and the flow of ideas was a team effort with all the different professionals commenting and adding information on various aspects. These comments were not restricted to the topics of their own professional field but also on overlapping of information between fields, especially in interrelated topics like the budget, construction limitations and spaces arrangement. Due to the design protocol and the strict process that the participants followed and the lack of any professional silos or time to brainstorm individually, all the ideas were subjected to criticism from the team. As a result, the decisions that were taken had to be accepted by all the participants and thus, to comply with the different professionals fields. This process led to an informed decision-making and resulted in fewer iterations during the conceptual design.

7.3 Summary and Feedback

The particular study provided an initial but thorough feedback on the Protocol and the design software. The activities taking place during conceptual design were monitored and the impact of the CDSP and TUIs during the study was examined. Furthermore, the team members were comprised out of fully qualified professionals, thus simulating a real-life feasibility stage.

When considering the overall process the team followed, it became prominent that their process followed closely the CDSP, leading to an end result through intense collaborative, conceptual, perceptual and physical activities. Design consensus was achieved for the final design solution and all the different discipline perspectives were taken into consideration. The multidisciplinary approach led to an informed design, but the process was not overly smooth, since the professional silos of the represented participants posed barriers. Even though, the collaborative and conceptual activities were very strong and they were reaching out to their colleagues for their opinions and the occurring argumentations had a constructive approach. **As the team members acknowledged during the study "the last two hours were really productive" with the reason being that they used a different process than they have ever had before.**

Regarding the M.S. PixelSense, the study participants were impressed with the capabilities of the TUI, especially the two professionals with the greater experience. They considered that the application had potentials for being applicable to the industry and solving problems related to multidisciplinary collaboration. Additional observations include the type of professionals engaged with the TUI; the design focus of the interface that is currently restricted to drawing related activities limits its use to design related professionals, like the architects, architectural technologists or structural engineers, not allowing non-design focused professionals to creatively engage with it. This obstacle could be tackled by introducing additional digital means and different types of interfaces especially for the non-designers. An enhanced communication between graphic user interfaces and TUIs could be a possible solution. Furthermore, the protocol analysis suggests that the TUIs enable a smooth design and cognition continuum resulting in enhanced ideas generation by allowing easier ideas externalisation. The users consider the process as a game, thus leading to increased communication, creativity and problem solving activities, even though they are still restricted by the design brief and aims of the design project.

The output that informed the third study considered the aspects on further improvements with the design software, allowing for a more intense design process and less technical problems, thus promoting even smoother human computer interactions and participants' communication. What is more, an important feature that had to be added to the process was transferring the design decisions in initial BIM drawings in order to monitor the transition from the conceptual design to detailed design. Eventually, the final aspect for consideration was overcoming multidisciplinary difficulties and barriers that still plagued the second study. For that purpose, the third study utilised final year students, to monitor whether the AEC silos are established from a student or a professional level.

8 Study Three

Chapter 8 describes the findings of the third study, the application of the Conceptual Design Stages Protocol (CDSP) and of the developed computational tool for examining the effects on conceptual collaborative design. Similarly to the previous two studies, this one follows a multidisciplinary team, from handing a design brief to undertake a feasibility work stage, up to a final discussion and questionnaires' feedback. Although the first and second study took place among a multidisciplinary team of AEC professionals, this time the study is following a multidisciplinary team of final year students of the AEC industry that were asked to follow the CDSP, to employ an updated version of the M.S. PixelSense and eventually to develop their conceptual solution and to make the transfer to BIM programs.

The first section of the chapter defines the setting of the study, its components and structure, physical and digital design tools. The second section describes the different levels of analysis, from the activities mapping to analytical actions' coding and to descriptions of the different numbers of segments and stages. That section closes with the self-evaluation tool explanation, the questionnaires feedback and the end-discussion comments. Finally, a short summary describes the key points of the particular chapter.

8.1 Method: Studies Components

The third study examined the Conceptual Design Stages Protocol application and the effects of the developed and updated computational design application on the conceptual design. Following the process developed by the two previous studies, during the third one the participants were equipped with physical and digital design mediums and media for developing their conceptual design ideas. The team was comprised out of different disciplines and the key components of the study are summarised in Table 8.1. Additionally, the design brief, the Moderator's presentation, the questionnaires and the evaluation tools can be found in **Appendix F.**

Table 8.1 Third study components

Design Task	▪ Design a workshop and research base for Postgraduates in the fields of Architecture and Built Environment Design: from architecture and architectural technology to quantity and building surveying and construction management.
Participants	▪ Two architects, a quantity surveyor, a building surveyor, an architectural technologist
Means	▪ Physical means (pens and tracing paper, maps' printouts, pictures, post-its, magnetic board) ▪ Digital means (laptop, desktop, M.S. PixelSense)
Method	▪ The proposed CDSP and transfer of the decisions to Revit
Monitoring	▪ Two recording cameras, a digital camera, questionnaires, end-discussion and evaluation tool
Aspects to be examined	▪ Multidisciplinary working ▪ Conceptual design stages ▪ Interactions with digital means ▪ Study's design process ▪ Integration of BIM
Critical Situations	▪ Application of the CDSP ▪ Interactions with the TUI
Anticipated outcomes	▪ Technical problems ▪ Evaluation of the CDSP ▪ Evaluation of the computational tool

8.1.1 Participants and Study Group Formation

For the third study, the recruited participants were comprised of last year students of Scott Sutherland School of Architecture and Built Environment. The team was comprised of five students, two architects, a quantity surveyor (Q.S.), a building surveyor (B.S.) and an architectural technologist (A.T.) (Figure 8.1). They partially knew each other from beforehand and they were all about to graduate while all of them had already some professional experience in practices. The purpose for recruiting students for the final study was to monitor the professional silos and how communication flows would be affected by multidisciplinary collaboration.

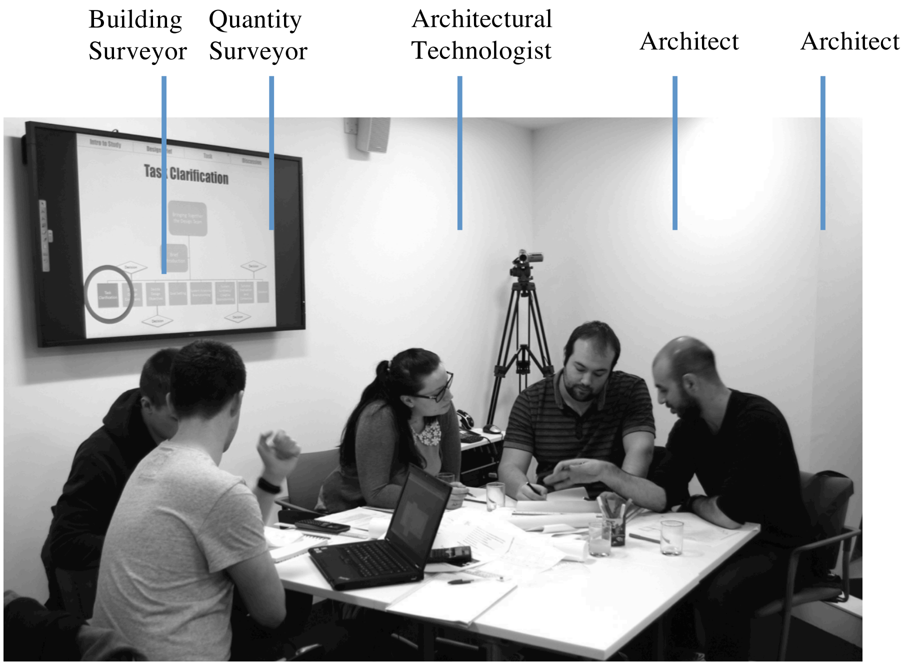


Figure 8.1 The multidisciplinary design team

8.1.2 Brainstorming Tools

The participants were provided with a range of physical and digital tools similarly to the two previous studies, including drafting and drawing tools, a flip-chart painting surface, tracing paper, pencils, markers and maps of the area specified in the design brief. Moreover, brainstorming tools were also available, like post-its and the magnetic board with the hexagonal pieces for mind mapping purposes. A laptop was provided with Internet access and relevant software was installed, i.e. Microsoft Excel for calculations, Revit and AutoCAD. The TUI was the M.S. PixelSense with the updated conceptual design application. The digital means and design mediums were utilised at different stages and parts of the study, likewise to the previous two studies, and they are categorised in greater detail in Table 8.2.

Table 8.2 Digital media and design mediums during the 2nd and 3rd part of the third study

Digital media and design mediums	2nd Part of the study		3rd Part of the Study
	1st Stage	2nd Stage	
Hand-draw sketches	+		+
Internet resources	+	+	+
Site information (pictures)	+	+	+
Site Drawings	+	+	+
Digital Sketches		+	+
Inserting pictures		+	+
Integration of physical and digital		+	+
Merging with other programs		+	+
BIM integration			+

The third study had a few differences with the previous ones regarding the multitouch display and the available types of software. The M.S. PixelSense design application that was initially tested in Study 2 was further developed to resolve bugs in the program and allow smoother interactions of the users with the TUI. The application kept the features that were developed for Study 2 and these were updated to run in a more smooth way. Additionally, the actions buttons' design was updated and further actions were added. The actions' taskbar is presented in Figure 8.2 and it includes importing pictures from the internet, importing pictures from a library with a depository of educational buildings, taking snapshots, keeping notes, drawing, erasing lines, cleaning the canvas and starting a new one. Problems that were monitored during the previous study, regarding drawing with layers, were solved with this version. The colour-picking tool was updated as well, to better reflect the creative process (Figure 8.3).

The images library was developed for Study 2 and was further updated by the moderator to include more examples of educational buildings. The library was developed to further support the brainstorming process and to provide a source of inspiration and information for study participants; the library window is depicted in Figure 8.4. These examples were partially presented during the task introduction and are included in Appendix F. Participants had also the option to draw on top of pictures, layer them accordingly and complete a range of actions on top of them, like erasing the drawn lines, de-activating the imported picture thus making it transparent or deleting it (Figure 8.5). The options of moving them around, rotating and scaling them were available already from the previous version as tested in Study 2.

Figure 8.2 The actions' depository of the updated computational design application

Figure 8.3 Paint tool (colour picking)

Figure 8.4 Images library

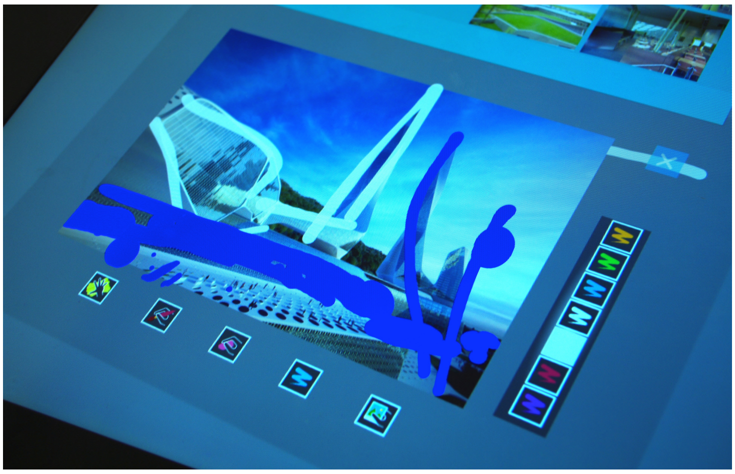


Figure 8.5 Drawing on top of a picture and available actions

8.1.3 Study's Structure and Design Mediums

The Third Study was divided into three parts and two further stages within the second part, as illustrated in Figure 8.6. The structure followed the examples of Study One and Two with the exception of the third part, regarding final decisions. The study initiated with an introduction to the task and a short ice-breaker for the participants to familiarise themselves, followed by handing the design brief and explaining the conceptual design task. The moderator also introduced the Conceptual Design Stages Protocol at that stage and provided instructions regarding its application for the study duration. The educational building examples were also presented and the participants initiated immediately the design process and inspected the design brief, the maps and data provided in the execution plan/ brief. The parts and stages had certain time slots/duration and the study moderator was informing the group on their available time to complete the task within three hours.

During the Third Study the design brief was simplified in a smaller educational building to facilitate for the students' capacities, thus allowing them to complete the task within the given time limitations. The brief was not lacking information though, following the good feedback from the previous study regarding the amount of details. The design brief was formed into a project execution plan and it included the involved parties, budget restrictions and scope of the project with the deliverables, the project description and the space requirements. Furthermore, site and area information was also provided together with number of expected occupants and information on some basic regulations to comply with. The design brief is attached in Appendix F.

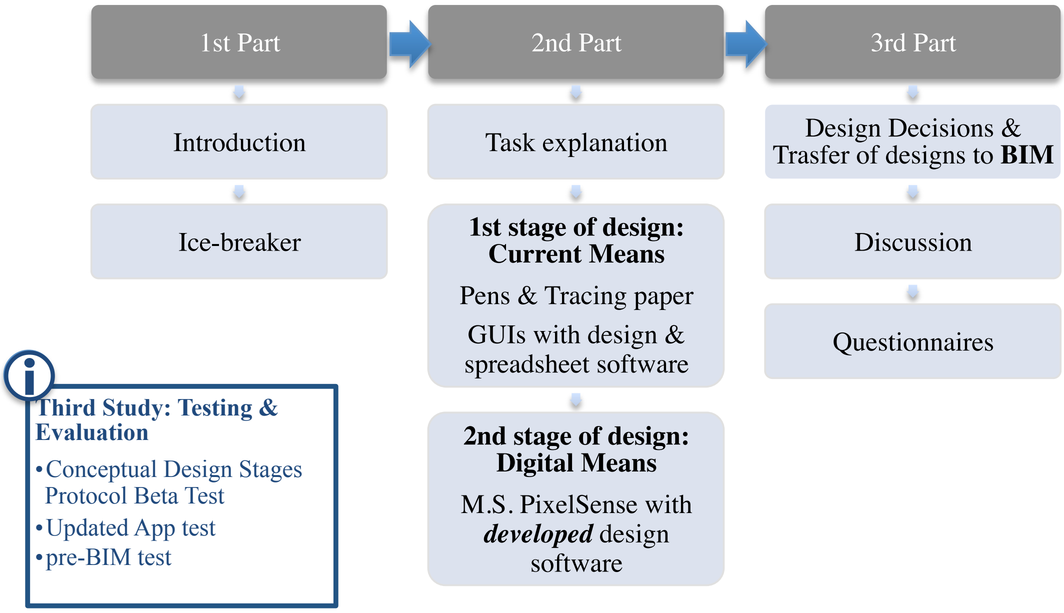


Figure 8.6 Parts and stages of the third study

The team started the design process immediately after the introduction and during this stage they utilised current means available to AEC practices, like pens, pencils and tracing paper, maps' printouts, pictures and printouts of the project execution plan. They were also provided with the option to use Internet resources and other types of commercial available software. The second stage of that part included the introduction and design by employing the M.S. PixelSense and the updated design application. The process further continued during the third part, where the design decisions were transferred to BIM and design finalisation followed. The different parts and stages according to the available design mediums and digital media are demonstrated in Figures 8.6 – 8.9.

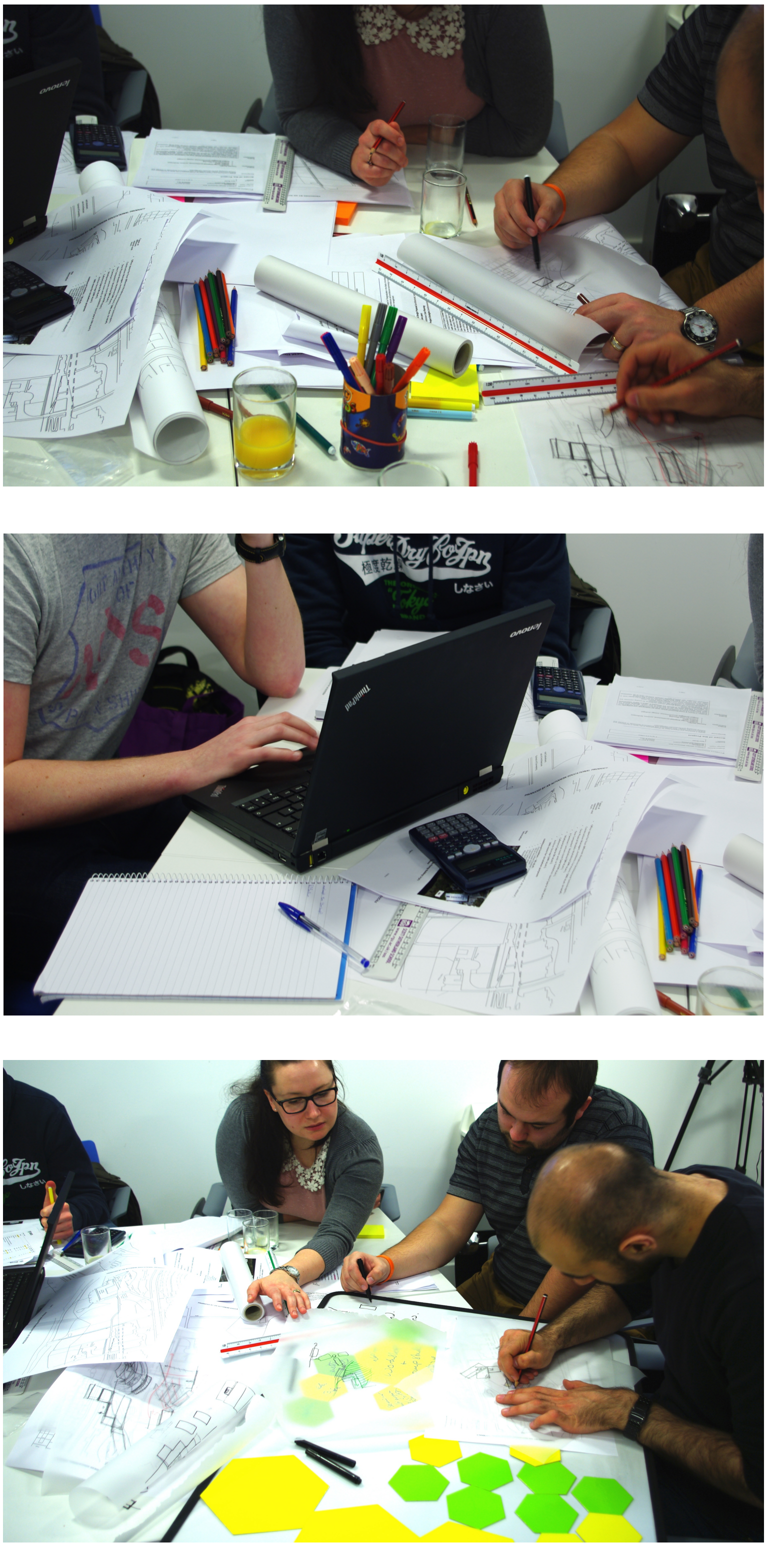
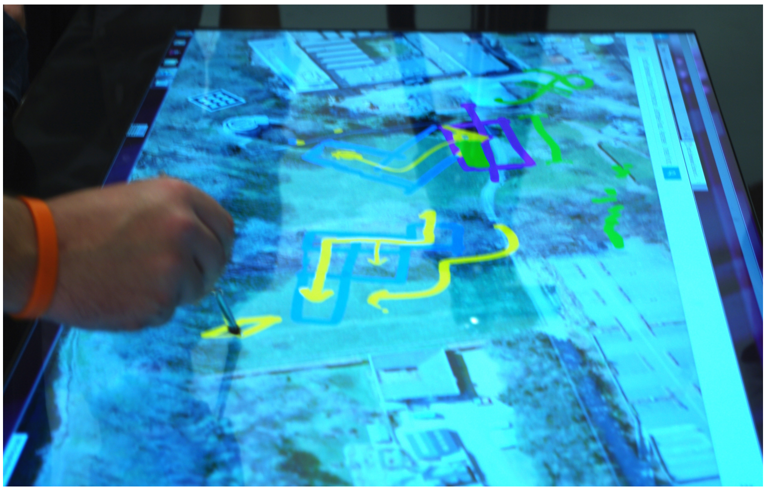


Figure 8.7 Third Study: 1st stage of second part, use of tracing paper and drafting tools, utilisation of spreadsheet software and Internet resources and of the magnetic board for brainstorming



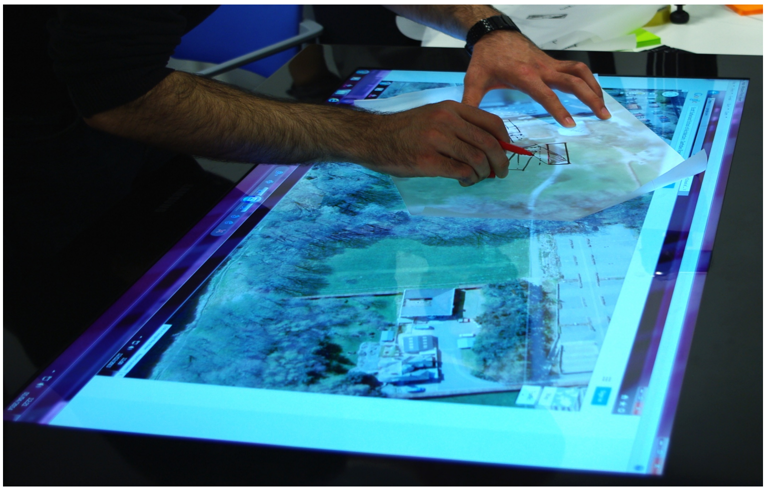


Figure 8.8 Third Study: 2nd Stage of second part, use of M.S. PixelSense design software and hybrid use with layering tracing paper

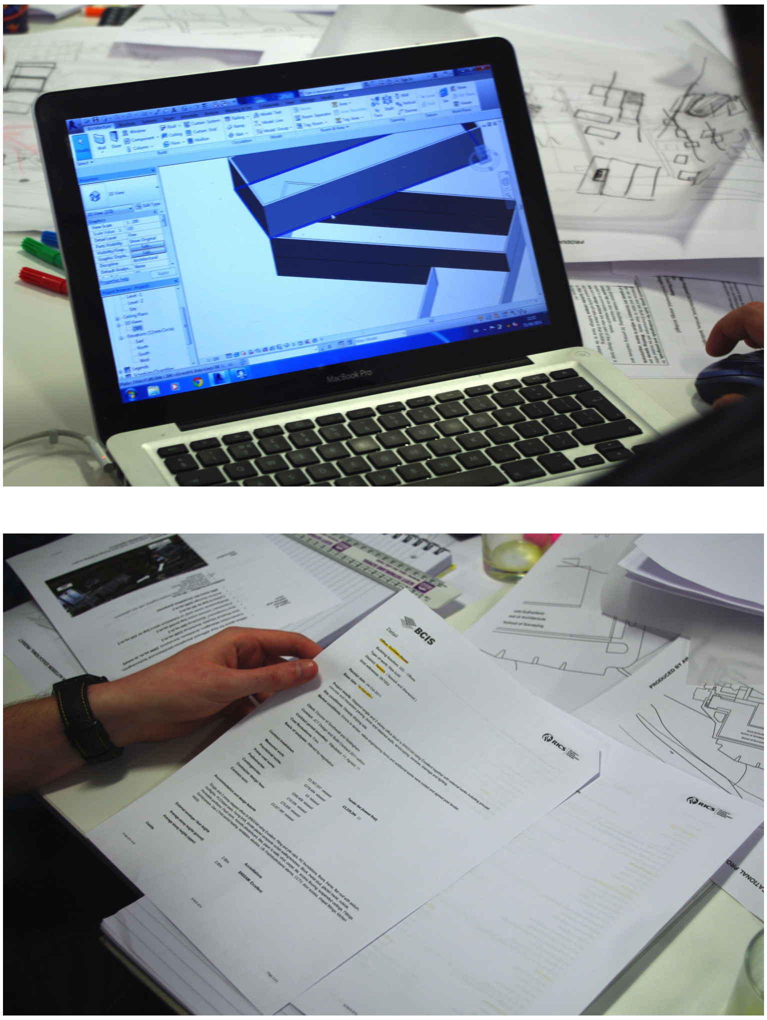


Figure 8.9 Third Study: third part, using Revit and spreadsheets for transferring the design and budget decisions into the initial steps of detailed design

8.2 *Results*

8.2.1 Experiment and Procedure

The Third Study shared a similar structure with the previous two and with some key differences. The study group participants were asked to implement the Conceptual Design Stages Protocol together with the updated TUI design application and import the produced concept into BIM. The fact that the participants were students led to a different approach than the previous two studies, with a more hands-on attitude from the beginning and a focus on the design from the very beginning. Furthermore, the communication among the multidisciplinary participants was the smoothest among all three studies, with a good flow of information between them regarding the different aspects of the project.

The design activities were very intense and they managed to decide on a concept that all of them were agreeing on and that was also answering to the project requirements, at least according to their background and knowledge. The participants were also motivated by the M.S. PixelSense design application and they had the shortest learning curve regarding the design interface compared to all the study groups.

8.2.2 Protocol Analysis: Activities Mapping

The first level of analysis focuses on mapping the activities that the team followed within the duration of the study. The particular method is analysed in section 4.6. Based on that method, an activities map was created, as presented in Figure 8.10. The third study's activities mapping showcased a different approach compared to the previous two studies. Once again, the chart followed the step of the given predefined Conceptual Design Stages Protocol and it monitored how closely the team of participants followed the CDSP or whether they adapted it to their requirements. Further feedback on the process is provided in the questionnaires section of the chapter.

Shortly after the introductory first part of the study, the second part initiated with the participants having already familiarised themselves with the available design mediums, they were examining the details of the design brief and taking notes of information they considered important. During the beginning of the first stage of the second part, communication was limited to individual inspections of the design brief. Shortly after, the architects and AT started designing while the Q.S. and B.S. were exploring aspects relevant to cost. The discussions were following a system synthesis and brainstorming process straight for the beginning, with discussions about forms, shapes and spaces connections and locations being discussed from the start, accompanied by sketches and notes. The team commenced the study with a holistic approach to their conceptual design process by considering multiple steps at the same time, including discussing on possible solutions, sketching and synthesising their ideas and afterwards comparing them to the objectives as set by the design brief. They did not question the design brief and, additionally, they did not add further information to it or try to clarify aspects. Communication among the participants was intense straight from the beginning as well, with all the different disciplines participating and questions being asked among them for clarifications on topics like the budget, the building's potential shapes and building regulations.

The moderator prompted the participants to utilise the M.S. PixelSense for their design explorations during the second stage of the second part of the study. The team had already found a basic form, an initial budget and other design details, features relevant to the circulation space, interior space and cost limitations. An introduction to the TUI assisted the team to make a smoother transition to the design environment and they initiated using the design application with a great ease. The team kept analysing the conceptual ideas during that stage, with a greater multidisciplinary communication this time, since the environment allowed for a shared understanding of the designs. Both 2D and 3D visualisations of the ideas together with intense dialogues among them assisted in communicating the concepts of the design and promoted questions and further clarifications of the developed ideas, together with greater elaboration on non-clarified topics, regarding the levels, people's flow and constructability. Perceptual activities were enhanced due to shared understanding of the ideas through the M.S. PixelSense and collaboration was promoted. During that stage, many different issues with their concepts were resolved, design decisions were taken and by the end of that stage they were ready to make a leap in design and transfer their concepts in BIM software.

Eventually, the third part of the study was focused on finalising the conceptual design, transferring the information into BIM and reflecting back on the whole duration of the study. During this part, intense negotiations took place among the different disciplines for finalising design, constructability and cost, while design problems occurred due to the greater detail of design. These problems were acknowledged as part of the detailed design and soon after the study came to a halt since the conceptual design was completed.

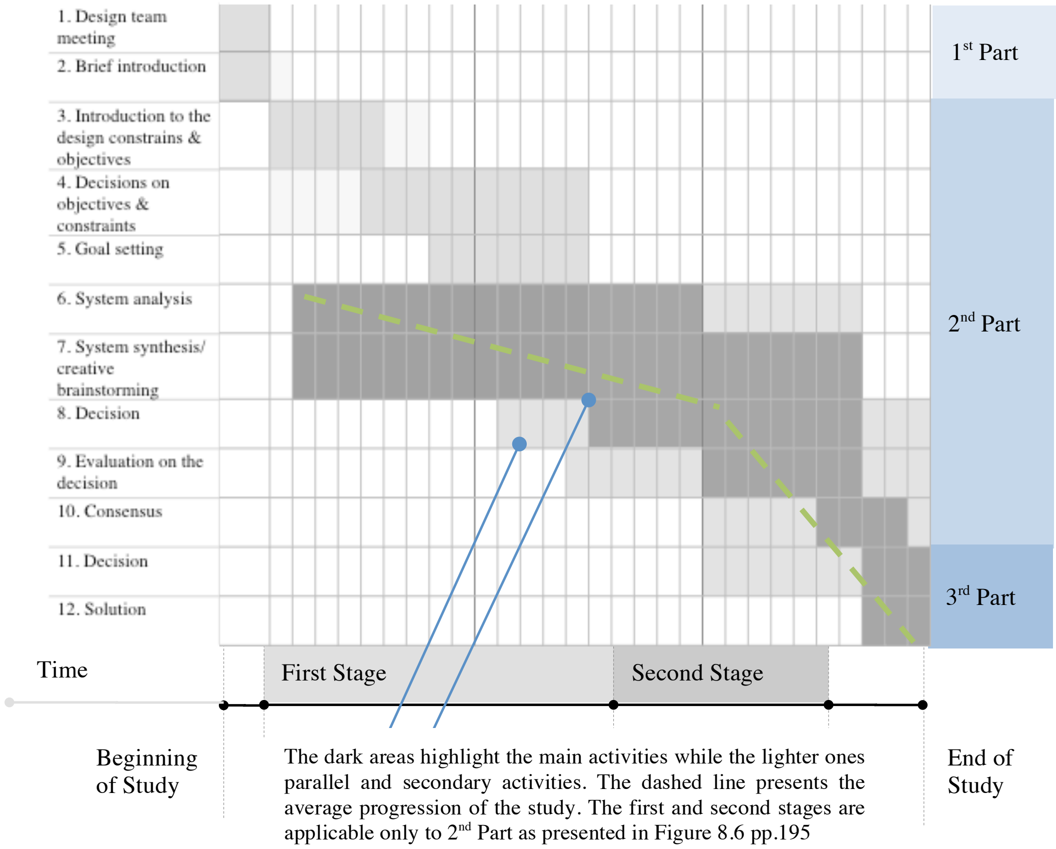


Figure 8.10 The design activity during the third study

The team was comprised out of last year students, with some professional experience, one of the architects was working part time while completing his studies, while the others had practiced as part of their studies. Even though their limited experience, they followed a professional methodology for completing the design problem. The limitations on their experience was evident from the beginning, with the process initiating straight from the system synthesis and analysis instead of clarifying their objectives and constraints from the beginning. They managed to cover up though since during the brainstorming process they were making often iterations between brainstorming, reflection of the design brief and possible restrictions. The open communication among them also made up for the lack of experience; the design was partially led by the architects but with open and free communication and collaboration among the different disciplines and a clear appreciation and acknowledgement of the multidisciplinary input.

The process was linear but it did not initiate from deciding on objectives and constraints as such, since the participants did not elaborate on the design brief in the beginning, rather they instantly started brainstorming on potential design solutions. The design objectives and constraints as specified from the project execution plan were guiding their decisions during the first half of the first stage. Soon after though, the team members were adapting that information according to their professional viewpoints and were adjusting the design objectives to their project. A reason for that is the lack of experience among the design team members. Multiple steps were being undertaken though simultaneously, including brainstorming and evaluation of their ideas while moving between deciding on design aspects and synthesising information. This process lasted for whole second part of the study and the final design consensus among the team members was achieved during the middle of the third part of the study.

8.2.3 Protocol Analysis: Actions' Coding/ 3rd Study's Narrative

The second level of analysis as described in section 4.5 is providing feedback on the participants' interactions among them and with the physical and digital media together with their cognitive, perceptual, conceptual and physical actions during each stage of the study according to the structure presented in Figure 8.6. The descriptions of the third study evolution are in italics and that data are analysed for providing the keywords mapping and statistical analysis in sections 8.2.4 and 8.2.5.

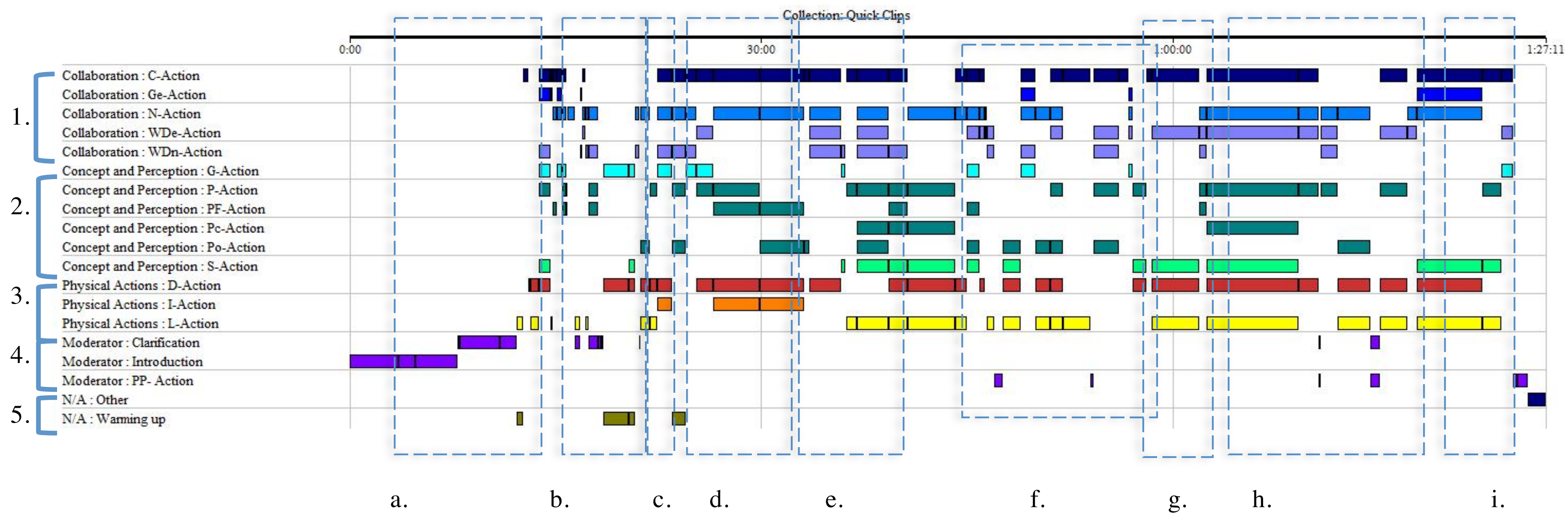
8.2.3.1 Actions' Coding for the First Stage of the Study

The third study started with an introduction from the moderator to the design task, the process that the participants were asked to follow, the different parts of the study and any additional details of the project, like specifications and regulations, budget of the project, and relevant examples of educational buildings. The participants were also introduced to the different types of design means, either the physical drawing mediums, or the digital media that were comprised out of the laptop and the M.S. PixelSense. A short ice-breaker assisted to the introductions among the participants, which was followed by further clarifications from the moderator regarding facilitation of the multidisciplinary work as reflected from their own experience. The moderator also provided the team with additional details regarding building regulations, size of the building and number of people to be facilitated in it and the introduction was concluded with the participants accommodating themselves to the work environment of the study.

The study group started promptly discussing possible design solutions regarding the landscape and space near the building, attractions of the site and possible passages to the location. All the students were participating during this dialogue and they were *actively collaborating and exchanging their ideas while they were drawing, inspecting and pointing elements like the design brief and maps. Preliminary ideas of possible building formations were developed with locations for the different types of spaces according to the design brief and strong collaboration included gestures, decisions on new aspects while designing. Negotiations between the different design students were taking place shortly after and further elaborations on the building form and potential problems within the site were discussed. The multidisciplinary input from the team members provided further suggestions regarding potential shapes and relevant environmental footprints. Clarifications took place among the team members with an agreement reached regarding their approach to the design task; the surveyors agreed to let the designers think of potential designs while they would be of assistance with cost estimations and potential constructability problems. From that point, the participants separated in two smaller groups, the designers and the surveyors, and intense collaboration was occurring within and between these two groups, with the designers evolving potential forms and the surveyors discussing information and researching for online resources. Communication between the two smaller groups consisted of information regarding number of storeys and the impact of the design ideas on cost.*

During the second half of the hour, the participants continued their task in greater detail and with more intense interdisciplinary negotiations. Shared representations and understanding among the designers with feedback from surveyors led to the development of initial sketches of the building. A connection between the costs, restrictions and the different spaces requirements was established and these negotiations led to redesign of the building form. Collaboration was occurring among the same discipline participants, with discussions and decisions on design aspects and on cost calculations. Further discussions among the designers on space connections stirred further negotiations among the whole group regarding rooms with potential double use, leading to further decisions on optimising their available space as described from the design brief, thus re-organising their space priorities. The magnetic board was also introduced at that point and the designers immediately incorporated it within their mind maps and space diagrams, connecting the pieces and making the connections between the hexagons representing the various types of spaces. The two smaller teams kept informing each other about their progression on numerous topics, like relevant examples of buildings, potential claddings and their cost and establishing a central core for the building for extra cost savings and easier constructability. The designers shared the hard copies of the drawings with the surveyors while the second ones handed their results to the designers. A quite vivid collaboration exchange of ideas was happening at that stage *that led to a renewed focus on the specifications of the building and the circulations spaces, leading to a fresh start of the design brainstorming.*

The last half hour of that first stage had long periods of collaboration, conceptual and physical activities that involved plans and cost clarifications. The two smaller teams worked separately for the first twenty minutes, with the designers clarifying plans and providing potential design solutions, negotiating and organising elements, comparing and evolving their design ideas and eventually deciding on new and existing features. On the other hand, the team of surveyors were discussing their findings, asking for clarifications from the moderator, analysing problems that were occurring with their estimations and, finally, moving quickly with their task. The two groups worked in parallel during that period of time, with often breaks for exchange of information between the two groups. Towards the end of that half hour the two teams came together to examine their ideas and solutions, with the team of designers updating the surveyors on new information on circulation space, interior organisation of different spaces and the core of the building, while the surveyors were asking questions on these topics. Furthermore, the surveyors were providing information on issues relevant to the budget of the project and to project's adaptation to regulations. The duration of the first stage according to actions' coding is depicted in Figure 8.11.



a. Introduction and Clarifications

b. Development of preliminary ideas

c. Agreement for multidisciplinary working

d. Smaller groups formation

e. Multidisciplinary discussions

f. Use of magnetic board for brainstorming

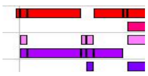
g. Screens' and drawings' sharing

h. Designers' and surveyors' teams work

i. Sharing information between teams

Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A



The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. It is apparent that collaboration is continuous during that stage with some fragments due to the lack of experience among the participants. Even though the slight fragmentation, collaborative actions are fully supported by a focus on the different project's features, decisions, brainstorming and design that initiates from the beginning of the study.

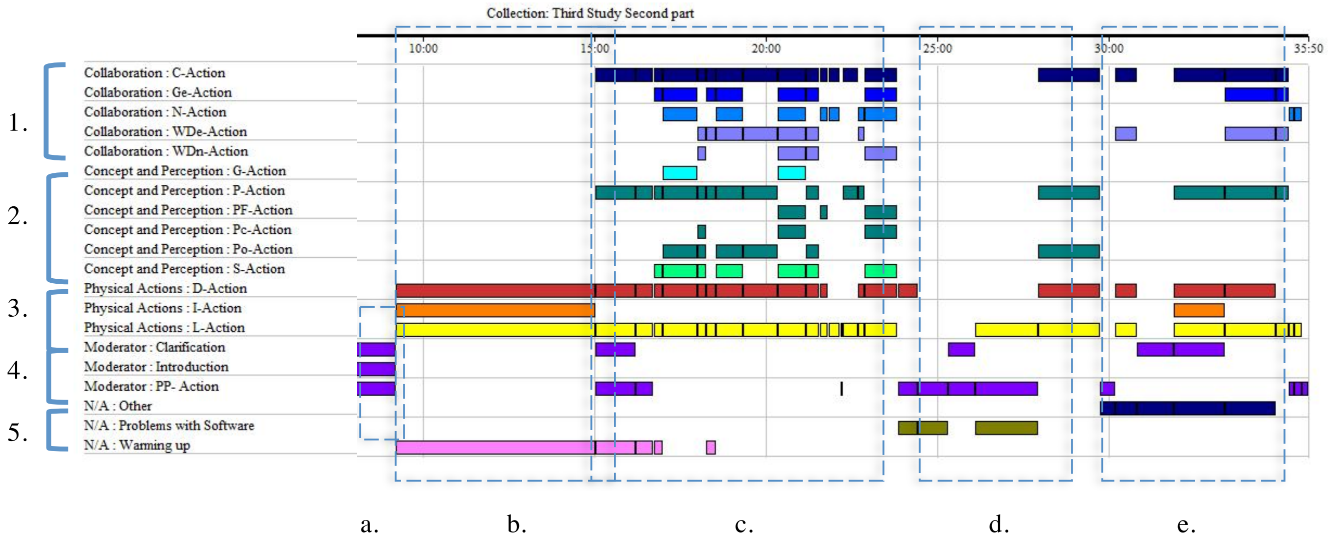
The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. During the particular stage the merging of the team members and the group formation occurs while discussions are more hesitant but the participants are willing to collaborate. Initial ideas are developed and the group is sharing their ideas and designs.

Figure 8.11 Third study: first stage keyword mapping

8.2.3.2 Actions' Coding for the Second Stage of the Study

The second stage commenced with an introduction to the TUI and the design application, a short demonstration of designing on top of the M.S. PixelSense and possible ways to utilise the different features of the software in relation to their designs. Following some questions and answers on technical issues, one of the architects immediately started designing their conceptual ideas. The moderator prompted the rest of the participants to test the interface and familiarise themselves with it. A warming up process assisted in acclimatising with the interface and the participants reproduced the design concepts that were developed up to that point. Immediately after, the team members decided to restate their ideas in order to make sure that consensus was reached to that point and that no information was left behind. A quite intense collaboration took place during that time, with clarifications provided from the different team members and perceptual activities taking place regarding different levels of the building. The strong communication allowed the team to fully understand the developed concept and to further negotiate and rethink multiple aspects of the project, like the different levels of the building in relation to the circulation space and the movement within the structure. The architects continued with describing, drawing and inspecting the types of spaces and *points of access for each floor level and they were sharing this understanding with the rest of the participants; therefore, the prevailing actions were gestures and decision taking for both new and existing ideas. The designers drew both 2D and 3D versions of the building for the purpose of making the design clearer for the surveyors of the team, while they were describing the volumes, the structure and the sections of the building. Further ideas that the team developed through this collaboration focused on the car park of the building, roof levels and fire exits; these topics led to supplementary discussions with the participants reaching eventually an agreement. At that point, the participants exclaimed "That's collaboration!" and "Job done", as they were pleased with their workflow and communication. What is more, the participants used with a remarkable ease the design application, dragging around the menu, picking buttons and drawing while describing their solutions.*

The team continued the discussions that were focused on building regulations and costs, while the architects commented to the surveyors that they had tried to be creative with rectangular shapes for cost purposes. Additional discussions and negotiations on issues like skylights, covering parts of the building with ground and sustainability took place shortly after, with the team focusing on existing features and deciding on these elements. A brief break for transferring the drawings to a different program on M.S. PixelSense allowed the team to layer their digital drawings with the physical ones they had produced during the first stage. The architects placed the physical sketches, drawn on tracing paper, on top of the TUI, thus merging the physical and digital design means and mediums. The design process initiated once again with the team developing a design of greater detail on tracing paper and moving back to the TUI and the design application, subsequently, to redesign the final ideas. During the design process on M.S. PixelSense participants utilised the layers feature to showcase the possibilities of their designs by drawing each level on different layer and rotating and transforming them accordingly. This allowed for smoother communication among the different disciplines, since an advanced level of understanding was achieved among the participants; surveyors fully understood the ideas of the designers and actively provided their feedback to the process. The participants at that point acknowledged the necessity to change scale and level of design detail and make a transfer to a CAD or BIM software. The moderator led the team back to the desks' space and encouraged the participants to move forward with their ideas' finalisation, therefore leading to the third part of the study. The duration of the second stage according to actions' coding is presented in Figure 8.12.



a. End of introduction and clarifications

b. Participants warming up

c. Multidisciplinary working

d. “Job Done” moment

e. Layering physical and digital sketches

Levels of Action Categories:
1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A

The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. The participants managed to exchange their ideas successfully. Technical problems though were interrupting the smooth continuation of the project development.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. The participants learnt how to use the software quite fast and they were developing their ideas while they were warming up. They also used the hybrid method observed in the previous study; to

Figure 8.12 Third study: second stage keyword mapping

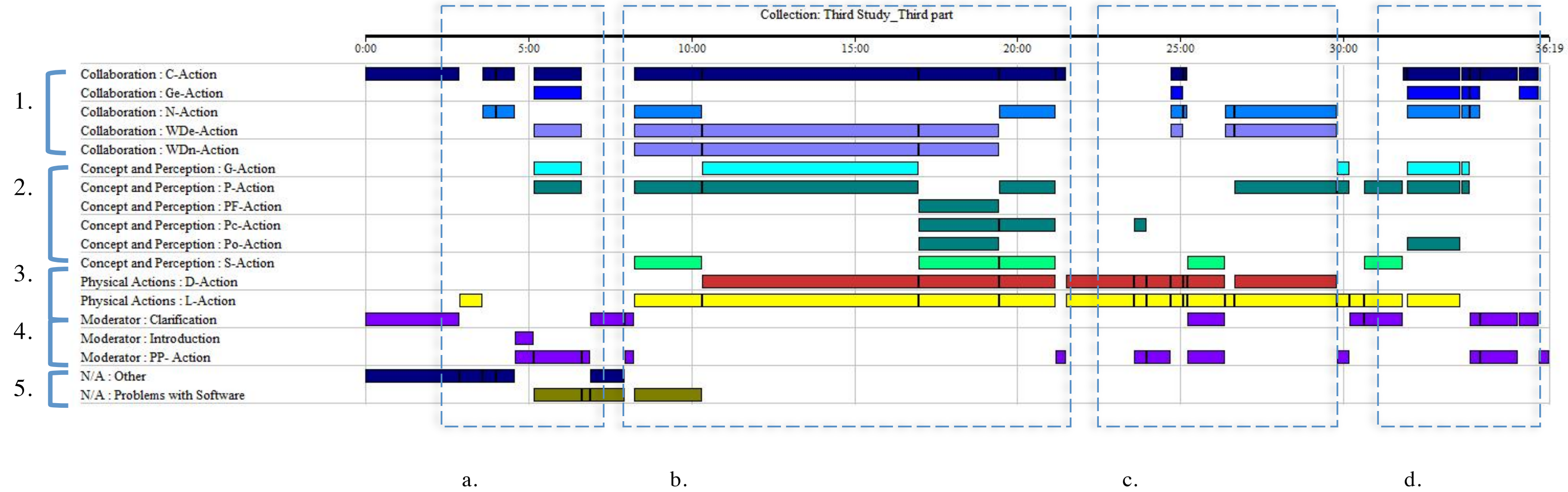
8.2.3.3 Actions' Coding for the Third Part of the Study

The third part of the study was comprised out of the finalisation of the conceptual design and the feedback to the study. The transition of the conceptual design to BIM and to excel spreadsheets that led to the conclusion of their design task took place in the beginning of that part. Following the M.S. PixelSense stage, the participants moved back to the desks and continued their discussions, this time though related to the transition to BIM, the connections of their designs with the available budget and the regulations that they had to comply with during their design. Surveyors further commented on the required adjustments in relation to the objectives of their project while the moderator was making sure that all of the participants shared the same information and they were on track regarding their task. The designers during that period faced some technical problems with the software they intended to use and they were discussing possible solutions to these problems. Shortly after though, the team was divided into the two smaller groups once again, with the surveyors initiating detailed excel spreadsheets with costs estimations and organising the relevant documentation of the project, while the designers overcame the technical difficulties and started their model in Revit. Both of these teams undertook their tasks on the available laptops, actively discussing their findings, negotiating decisions and ideas, brainstorming solutions to occurring problems and organising existing and potential elements. Eventually both of these teams were rapidly moving forward with the workflow.

The smaller team of designers transferred their hand-drawings in digital format that led to undertaking decisions on existing decisions while drawing and inspecting the produced design. Design speculations and reconsiderations were also taking place together with discussions on the dimensions and comparisons of elements, due to miscalculations within their sketches. The designers shared understanding of their ideas and were keenly collaborated and communicated their thoughts and designs. On the other hand, the surveyors' team continued their estimations according to the information on the design. The design process continued with interdisciplinary discussions regarding the construction of the building, potential materials and their environmental and aesthetic impact. Greater detail of information kept being added to the design, like walls, partitions and staircases based on their conceptual ideas while further evolving them and the design reached a satisfactory level of detailing for conceptual design.

Following the design conclusion, a new discussion took place between the two smaller teams, with the designers informing the surveyors on design clarifications to assist them with the cost estimations. These details concerned the volume of the building, the area development and dimensions. In the meantime, the surveyors provided further details and an active discussion took place among the participants regarding the concluded conceptual design. The surveyors additionally recognised the requirement for the production of detailed designs at that stage so to provide a more detailed estimation of the costs and any potential and not considered restrictions. The keyword mapping of the third part of the study is presented in Figure 8.13.

Overall, the team worked in a deeply collaborative manner, with no leaders within the group but with the acknowledgement of the design succession and the priority to the design with a deep consideration of the restrictions like the regulations, constructability and budget. The communication and respect of the opinions was the greatest among all the studies with a less argumentative tone and more a positive attitude to bridge the differences and find the best possible solution that the team was agreeing on. The moderator led the design to a conclusion, after making sure that the participants were pleased with the produced design and that they felt that it was answering to the design task and objectives set in the beginning of the study. A very interesting exchange of information occurred during the final discussions for achieving design consensus; the two different teams came together to share their findings and the process they followed was to share the screens of the laptops they were working on, and inspect the different elements as developed in different software.



a. Initial discussions on BIM and project's budget

b. BIM and spreadsheets preparations

c. Design brainstorming

d. Screen and final ideas' sharing

Levels of Action Categories:

1. Collaboration
2. Concept and Perception
3. Physical Actions
4. Moderator
5. N/A

The horizontal reading of the graph represent the different types of Actions occurring within the duration of the first stage of the study. *The actions' categories and coded names (like G-Action, C-Action and so on) are explained in Table 4.8 at page 100-101*. A smooth design activity was happening during that part of the study, with a number of decisions being taken from the designers and from the surveyors regarding the further evolution of the project. The process concluded with a collaborative screen sharing.

The vertical reading and boxes showcase the most important events that are described during the actions coding in a timely manner. The width of the boxes show the duration within the stage and the Actions encompassed within the boxes demonstrate the Actions that occurred during the described events. The two smaller teams focused immediately on transferring their decisions in greater detail, with some final discussions taking place during that part.

Figure 8.13 Third study: third part keyword mapping

8.2.4 Third Study: First and Second Stage Comparison

A comparison of the activities' duration in the two stages of the second part of the study showcased the differences between the use of physical design mediums and digital media. The conceptual design and collaborative activities were quite intense overall. The comparison between the two stages is presented in Figure 8.14.

The participants followed the process of Conceptual Design Stages Protocol overall. Their discussions regarding project's objectives and constraints was limited to the observation and discussion of the ones mentioned in the design brief, since due to their lack of experience they were not able to question beforehand the regulations and the project requirements. The team moved quickly to the brainstorming steps and the dynamics of the participants led them to separate to two smaller teams, the one of the designers and the one of the surveyors. This separation lasted for parts of the brainstorming session and the reason was for them to tackle faster the project requirements and face simultaneously design, cost and constructability issues. The process did work and the two smaller teams were coming together quite often to share opinions and understanding and to decide on different aspects of the project. Collaboration, negotiations and decisions on various new and developing ideas together with intense design and inspection were the most prominent aspects of that stage, with durations that were lasting for 58% of the time for collaboration, 52% for negotiations, 32% for decisions making, 53% for design and 43% for inspection of design elements. Moderator's activities were quite low and subtle during that stage (lasting for 2% up to 8% of the time) and the process was moving forward rapidly and smoothly. Clarifications on the coding scheme used for the analysis is presented in section 4.5.2, Table 4.8, page 100-101.

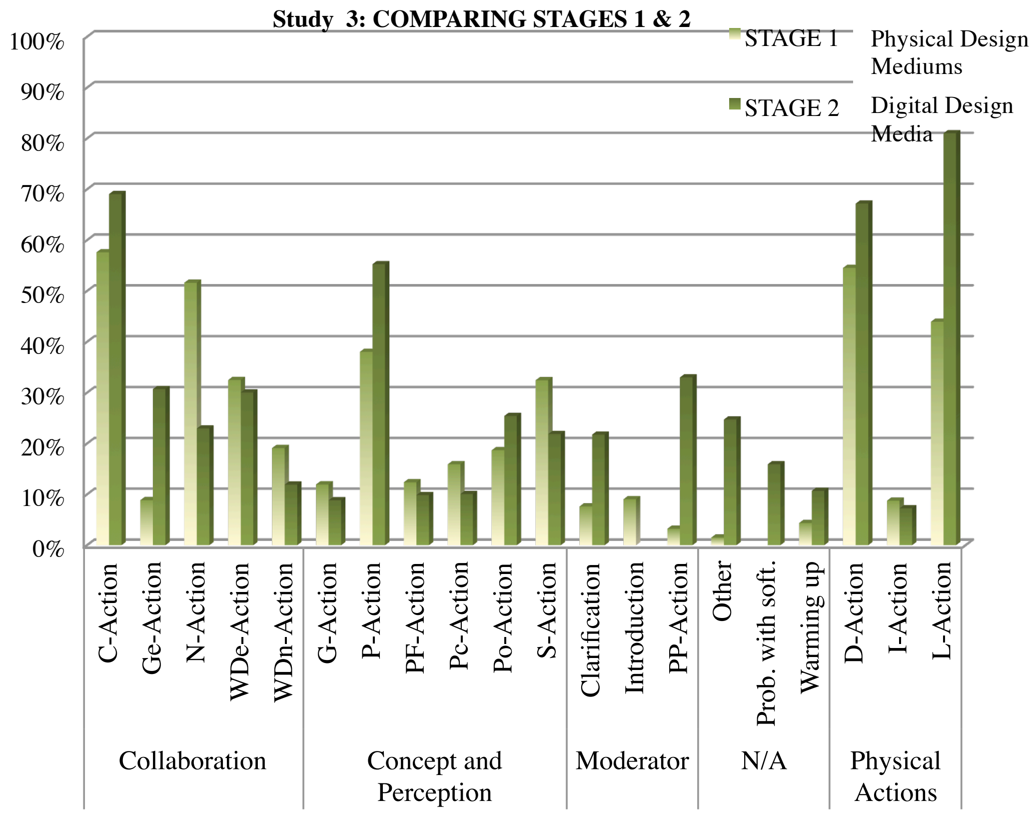


Figure 8.14 Comparing actions' duration for first and second stage of study 3

Overall during the first stage, the participants decided on various aspects of the project but the finalisation of their ideas occurred during the second stage, while using the M.S. PixelSense. The majority of the actions had an increased duration within the second stage, with the peak of percentages including collaboration, lasting for 69% of the stage duration, design and elements inspection with 64% and 80% accordingly, greater negotiations (52%) and brainstorming (53%). The participants focused around the tangible design surface that led to more active collaboration and vigorous ideas exchange while designing new and developed concepts. The actual design process on top of the TUI promoted their ideation process and the simultaneous multidisciplinary discussions. However, during that stage a number of technical problems occurred, which led to a greater interference of the moderator, with 21% of the time required for clarifications and

31% for promoting their design process and asking them to participate. Furthermore, the multidisciplinary dialogues even though intense, they were stalling at points, again an aspect that required the moderator to support the group for keeping it in track with the Conceptual Design Stages Protocol.

8.2.5 Duration of Segments

The participants spent an hour and forty-eight minutes on the two stages and additional thirty-six minutes for the third part of the study while transferring their decisions to initial BIM models. For the second part of the study that concerned the physical and digital media, the analysis was divided into 109 segments and the third part was divided into 32 segments, as illustrated in Table 8.3 and Table 8.4. The activities were happening in parallel; discussions were supported by system synthesis and sketching, thus allowing simultaneous perceptual, collaborative and physical activities. Graphs that compared the activities duration percentages and their relevant number of segments percentages for each stage and part of the study, supported the analysis of the relations between these two aspects for a clear understanding of their frequency during the study and for allowing further conclusions on the activities.

Table 8.3 Activities summary for study 3, stages 1 & 2

Actions		1st Stage of the Study		2nd Stage of the Study		Total time during the study	Total number of segments
Collaboration	C-Action	00:50:09	34	00:14:19	20	01:04:28	54
	Ge-Action	00:07:43	7	00:06:22	9	00:14:05	16
	N-Action	00:44:57	32	00:04:46	9	00:49:43	41
	WDe-Action	00:28:17	19	00:06:14	11	00:34:31	30
	WDn-Action	00:16:38	17	00:02:28	4	00:19:06	21
Concept and Perception	G-Action	00:10:24	13	00:01:50	2	00:12:14	15
	P-Action	00:33:07	21	00:11:28	15	00:44:35	36
	PF-Action	00:10:47	9	00:02:03	3	00:12:50	12
	Pc-Action	00:13:51	4	00:02:05	3	00:15:56	7
	Po-Action	00:16:16	11	00:05:16	6	00:21:32	17
	S-Action	00:28:15	13	00:04:32	7	00:32:47	20
Moderator	Clarification	00:06:38	12	00:04:31	4	00:11:09	16
	Introduction	00:07:52	3			00:07:52	3
	PP-Action	00:02:50	7	00:06:51	11	00:09:41	18

Actions		1st Stage of the Study		2nd Stage of the Study		Total time during the study	Total number of segments
N/A	Other	00:01:19	1	00:05:08	5	00:06:27	6
	Prob. with Soft.			00:03:18	3	00:03:18	3
	Warming up	00:03:49	4	00:02:13	4	00:06:01	8
Physical Actions	D-Action	00:47:30	26	00:13:56	19	01:01:26	45
	I-Action	00:07:38	3	00:01:30	1	00:09:08	4
	L-Action	00:38:16	23	00:16:48	25	00:55:04	48
3rd Study Duration and n. of segments (2nd Part)		01:27:04	78	00:20:44	31	01:47:48	109

Table 8.4 Activities summary for study 3, part 3

Actions		Duration	Number of Segments
Collaboration	C-Action	00:23:15	17
	Ge-Action	00:04:42	6
	N-Action	00:10:58	11
	WDe-Action	00:16:28	7
	WDn-Action	00:11:11	3
Concept and Perception	G-Action	00:10:25	5
	P-Action	00:18:33	9
	PF-Action	00:02:28	1
	Pc-Action	00:04:33	3
	Po-Action	00:04:07	2
	S-Action	00:08:38	5
Moderator	Clarification	00:09:07	9
	Introduction	00:00:33	1
	PP-Action	00:07:24	12
N/A	Other	00:05:38	5
	Prob. with Soft.	00:04:53	4
Physical Actions	D-Action	00:18:47	10
	L-Action	00:25:35	17
Duration and n. of segments for 3rd Part		00:36:15	32

Table 8.3 represents the raw data for both stages of the study that are further analysed in Figure 8.15; this Figure showcases the actions for the first stage of the study and compares two percentages for each action; the first one (blue points) is the duration

of the action during that stage as a percentage to the total duration of that study stage (01:27:04). The second type of percentages (red points) represents the number of segments where this action can be found (frequency of the action) during that stage as a percentage to the total number of segments (78) that were identified for that stage. Within the duration of the first stage collaborative actions, negotiations, focus on new and developing ideas, design brainstorming and ideas exchange over the developed sketches were the most prominent examples of activities with a longer duration and shorter intervals. The reason for that was that the participants were focusing on different aspects of the project for longer periods until an initial decision could be drawn. Furthermore, the introduction shared the same characteristics since it was essential for the moderator to set the context for the participants though a longer introductory presentation. Less actions shared the opposite characteristics of shorter duration in greater number of segments, and these were mostly related to actions relevant to the moderator, like providing clarifications and keeping the team on track. Further clarifications on the used coding scheme are presented in section 4.5.2, Table 4.8, page 100-101.

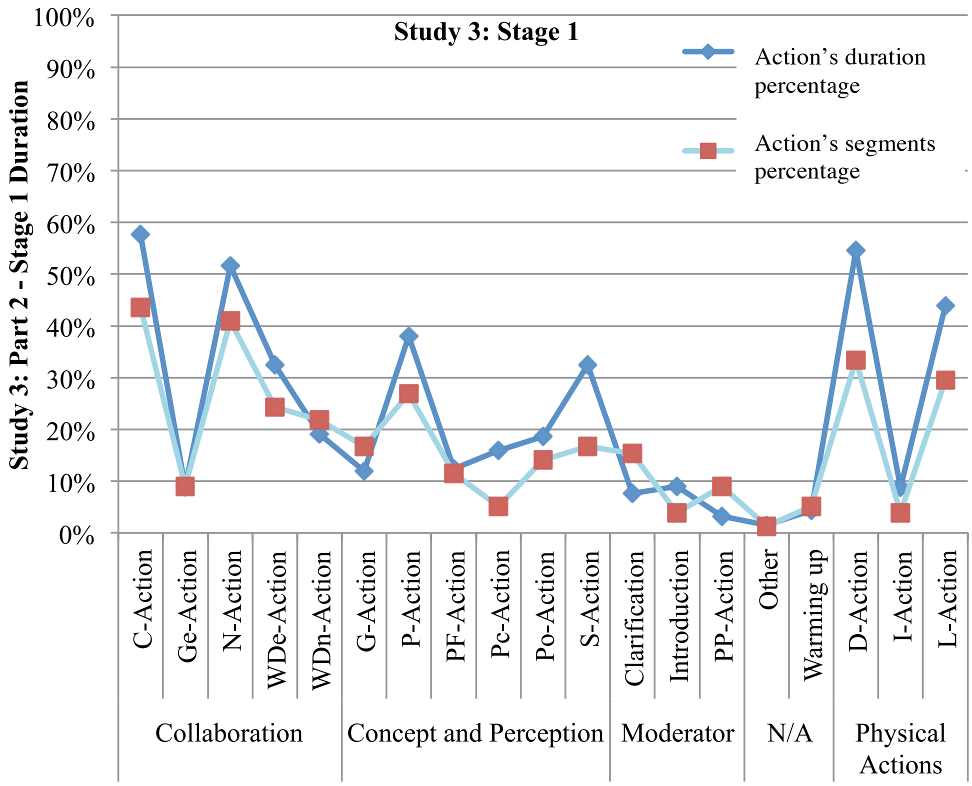


Figure 8.15 Study 3, Stage 1, comparison of percentages between actions duration and number of segments

Interestingly, during the second stage of the study most of the activities shared the same percentage of segments and duration. Figure 8.16 compares two percentages for each action, the action's duration and frequency; the blue point represents the action's duration as a percentage to the duration of that stage (00:20:44) while the red point showcases the frequency of the action as a percentage of its occurrence within this stage's segments (31). Conceptual activities of brainstorming and comparing different design solutions were the ones with the longer duration over a smaller number of segments while the decisions workflow and negotiations were shorter in duration but more often. All the rest of the actions were characterised by an even percentage of duration and segments. The particular indications showcased the immediate nature of the physical and conceptual actions, thus permitting a more intuitive design approach due to the nature of the tangible surface. In other words, the TUI allowed the participants a greater flexibility in expressing their concepts both verbally and physically, and allowed a faster transition between concepts and representations.

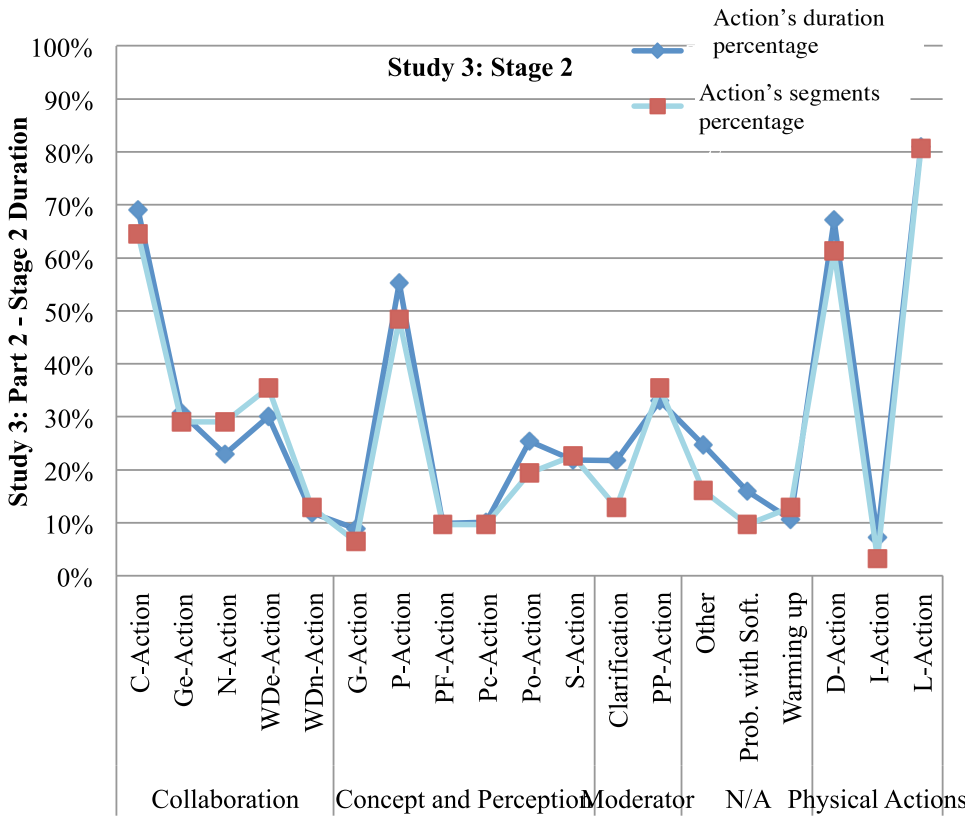


Figure 8.16 Study 3, Stage 2, comparison of percentages between actions duration and number of segments

The third part of the study included collaborative, brainstorming, conceptual, perceptual and physical actions like the previous stages since it was part of the development of the conceptual design. The percentages of the third part of the study are presented in Figure 8.17. The two percentages for each action, the action's duration and frequency, are represented with the blue points, with the duration of that part lasting for 00:36:15, and with red points, with the third part being divided in 32 segments. This part of the study shared analogous features to the previous two stages, with most of the activities lasting for longer period of time and in shorter intervals. The greatest difference between these percentages was observed for setting goals and taking decisions for new and developing ideas, organise elements of the design solution and moving forward with the design development. This difference among the percentages resonates with the third part of the study since it was focused on transferring the design decisions to BIM software. As a result, the participants had already taken most of their decisions and were making the transfer of their ideas to Revit. Discussions and shared understanding among all the participants was still part of the process due to the simultaneous approach of designing, negotiating and exchanging ideas and opinions on issues that were coming up because of the transfer to BIM. Most of the actions showcased a greater percentage of the time duration to the number of segments in varied percentage differences with the exception of actions relevant to moderator. As in previous stages, moderator intervals were more frequent for instructing and clarifying information and promoting the design process.

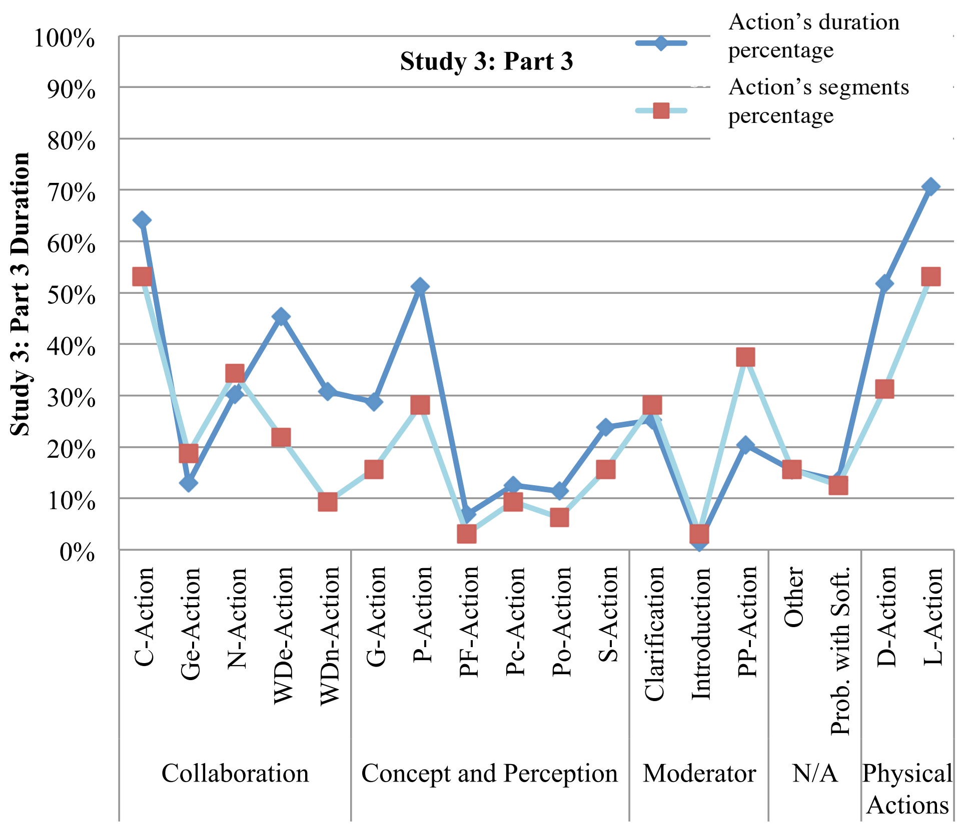


Figure 8.17 Study 3, Part 3, comparison of percentages between actions duration and number of segments

Eventually, the data presented in Tables 8.3 and 8.4 for the whole duration of the study brainstorming were visualised in Figure 8.18 based on their number of segments and with a clear reference to their duration. This illustration leads to a number of conclusions for the third study. First of all, collaboration and design related activities were the actions with the greatest duration and included in the larger number of segments, thus representing the main focus of this study. Negotiations among the participants, focus on existing and new features and relevant decisions were the actions that followed in number of segments and duration and that demonstrated the conceptual and collaborative nature of the study. The moderator's action of promoting and supporting the process was also quite prominent during this study, in contrast to the previous ones. Further actions included organising elements, gestures, and setting goals and the main characteristic of these ones is that even though gestures had smaller time duration, the number of segments was comparable to more substantial actions like setting goals, as it is observed in Figure 8.18. Similar features were shared by other actions, like comparing elements with a longer duration and warming up that had a shorter duration but it was observed in a larger number of segments.

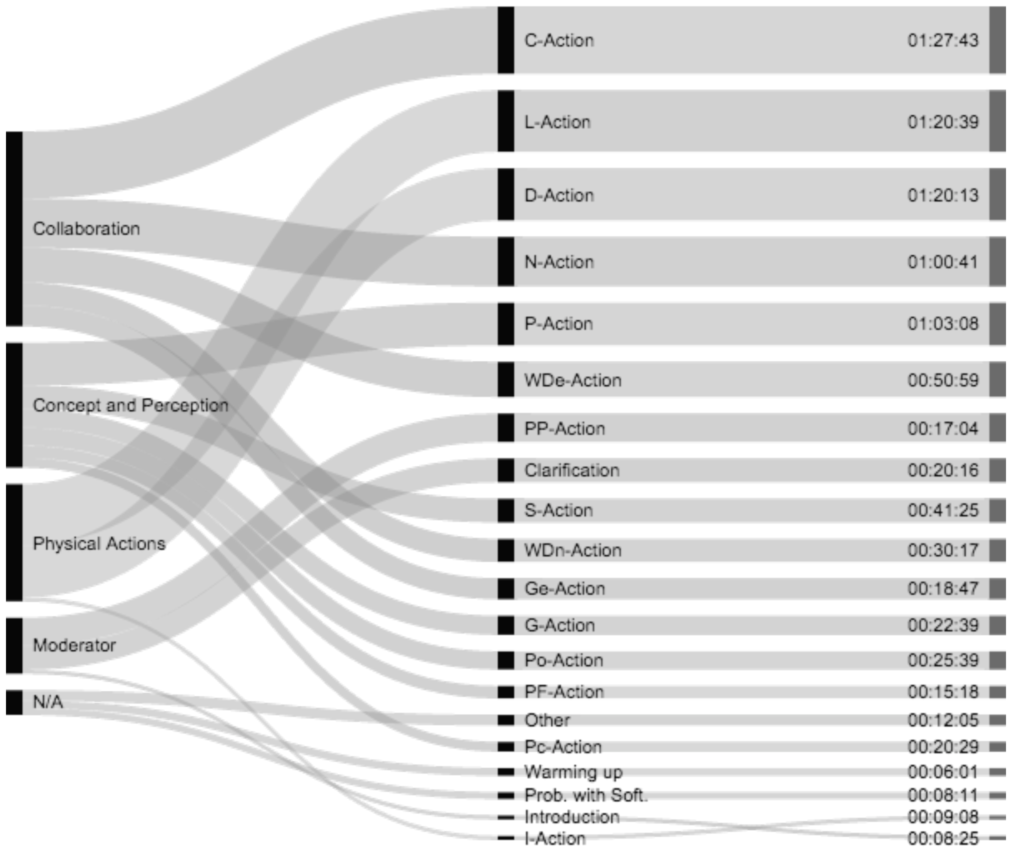


Figure 8.18 Actions' categorisation according to number of segments and time during the 3rd study

8.2.6 Self-Evaluation Tool

After the conclusion of the conceptual design, the team was asked to complete a self-evaluation tool for rating their completed design and the responses were individual. This step was followed by the completion of a questionnaire and the study closed with a short discussion. The self-evaluation tool was a method utilised during the second study as well, and it proved to be a valuable instrument for understanding the participants' opinion on the designs they produced.

For the most part, the team was pleased with functionality and impact aspects as represented in Figure 8.19 and Figure 8.20. The most successful features of their solution were relevant to the use of the building, the access, the organisation of spaces, the character of the designs and its integration within the context of the site. Average results were given for the form and material of their solution, the internal environment and performance, and low response was provided for construction and engineering systems. The evaluation reflected the process they followed, with the greatest focus given to the design and cost of the project and less on supportive aspects, like construction and materials. Furthermore, the team had developed ideas for interior space organisation, performance on the building and materials but they did not manage to transfer them to BIM due to time limitations.

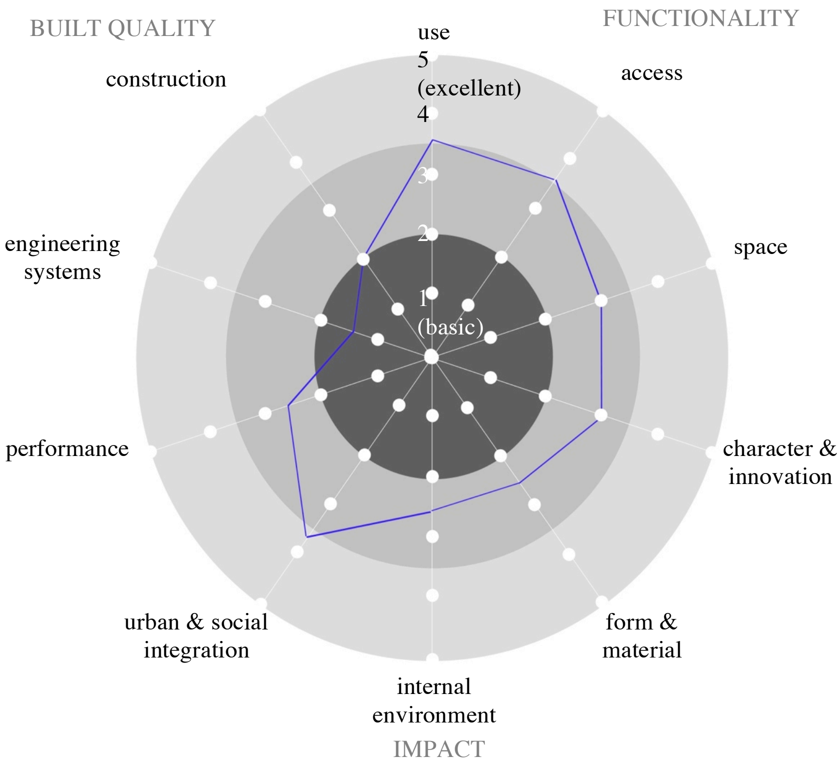


Figure 8.19 Self-evaluation tool, average responses for the 3rd study

Figure 8.20 represents the collected data and the different colours showcase the different replies to the evaluation tool. For the purposes of this research it was not required to identify the different professionals providing the answers, therefore Figure 8.20 showcases the raw data that were further analysed in Figure 8.21 according to their deviation.

Regarding the graph that exhibits the individual responses (Figure 8.20), it becomes prominent that most of the participants shared a similar opinion on the produced design with a relatively small deviation observed in the rest of the examined aspects. The greatest deviation of opinions was monitored for the internal environment, character, innovation and performance of the building, as it is observed from Figure 8.21. The reasons for that can be located to the multidisciplinary team formation that promoted a more holistic design approach and less focusing on more technical aspects. The surveyors provided the poorer evaluation of the concept and they considered that not enough attention was provided to the technical aspects of the solution. On the other hand, the most optimistic evaluations came from the architects; they were overall pleased with the solution. Interestingly, the participants were in agreement when rating most of the characteristics of their solution and they acknowledged that if they were provided with more time they would be able to answer most of the aspects in the evaluation tool.

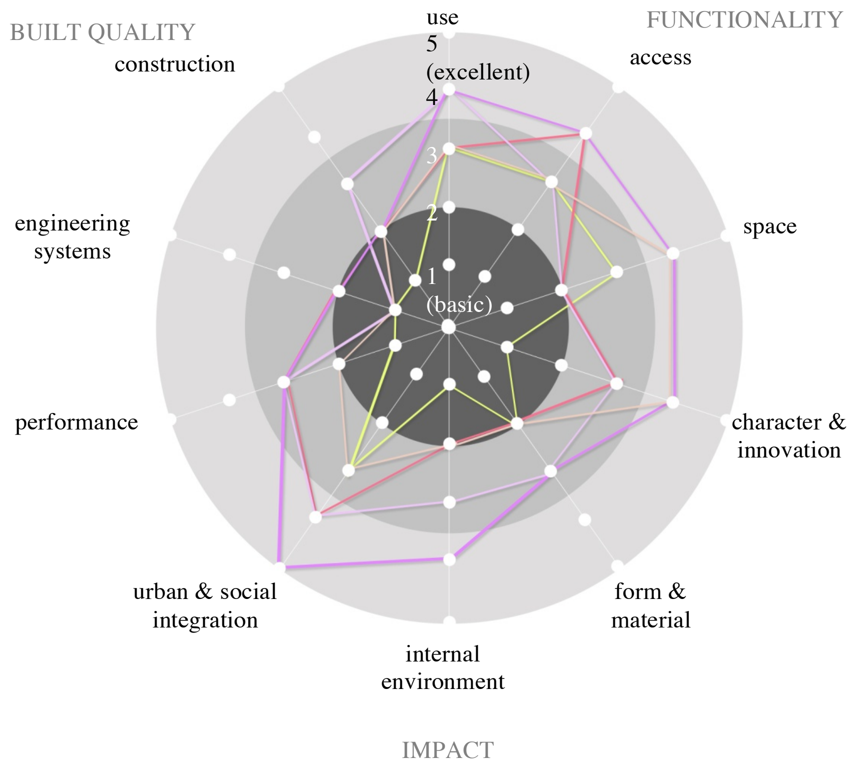


Figure 8.20 Self-evaluation tool, individual responses for the 3rd study (each colour represents one participant)

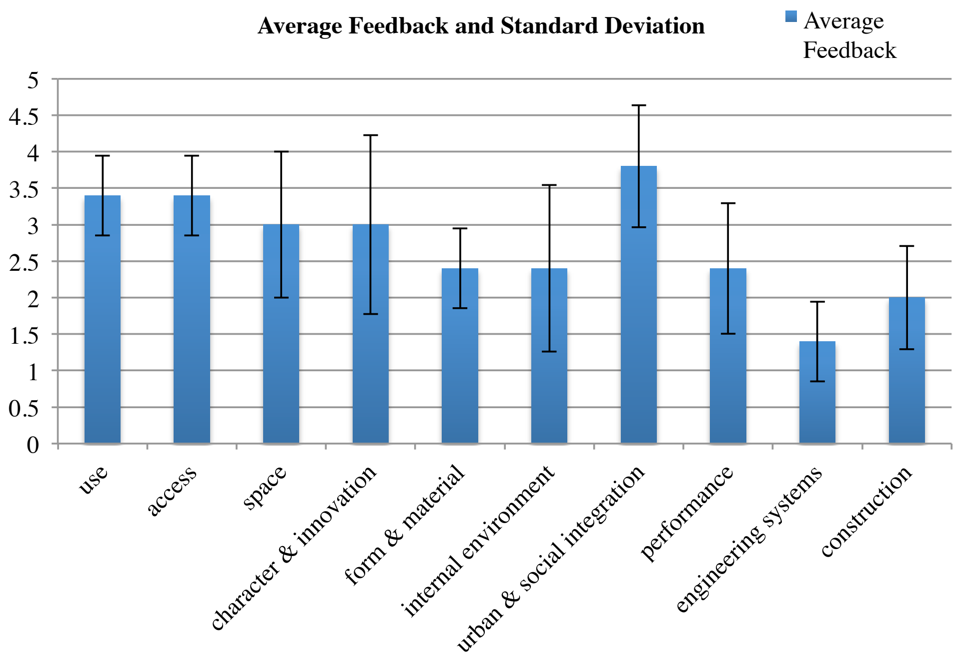


Figure 8.21 Self evaluation tool, average responses and standard deviation for the 3rd study

8.2.7 Questionnaires and End Discussion

Questionnaires that were asking for the overall experience during the study were distributed to the participants, following the evaluation of the produced solution. The purpose of the questionnaires was to provide additional feedback on various aspects, like former knowledge of the participants and their familiarity with digital means and processes. The first feature that was examined was their previous experience in conceptual design, with 60% of them having previous knowledge and experience of the process and 40% not having similar experience, while the percentages reflected the ratio between the designers and surveyors. The use of computers for any design stage was the second question, with the surveyors using computers frequently for cost estimations and materials measurement. On the other hand, the designers used computers frequently and always since it provided a greater flexibility for making design alternations (Figure 8.22). All of the participants agreed that they utilise computers from the beginning of a project and the early design stages and 60% of them answered that they also make use of sketches for supporting their design ideation, with the 40% of the surveyors answering that they are not using sketches since it is not applicable for their case. Identical percentages were the replies for the recognition of the initial ideas in final formal drawings; once again, designers responded that rather frequently are able to recognise their initial ideas but they acknowledged that due to restrictions or considerations ideas often require for developing (Figure 8.23). The preferred design mediums were divided in pen and paper for 60% of them, including the surveyors and one architect, while the 40% of the participants preferred design software, SketchUp and Revit in particular, with all of them keeping notes during concept stages (Figure 8.24).

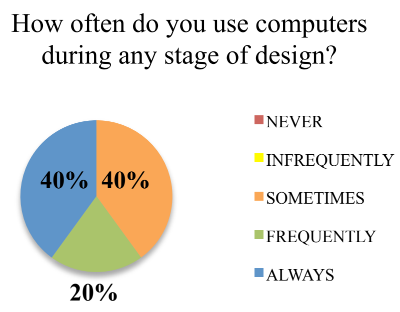


Figure 8.22 Frequency of computers' use

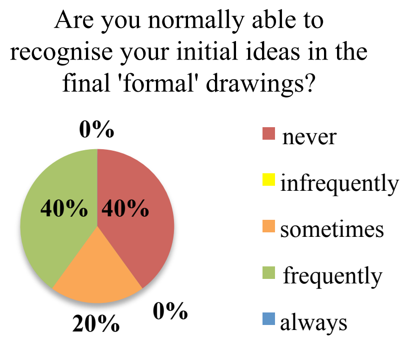


Figure 8.23 Ideas' recognition in final design

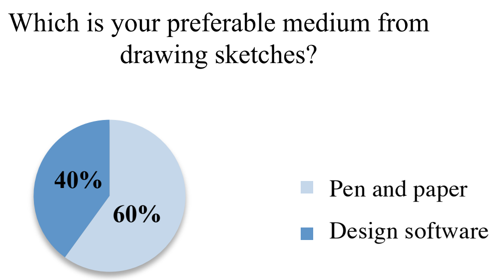
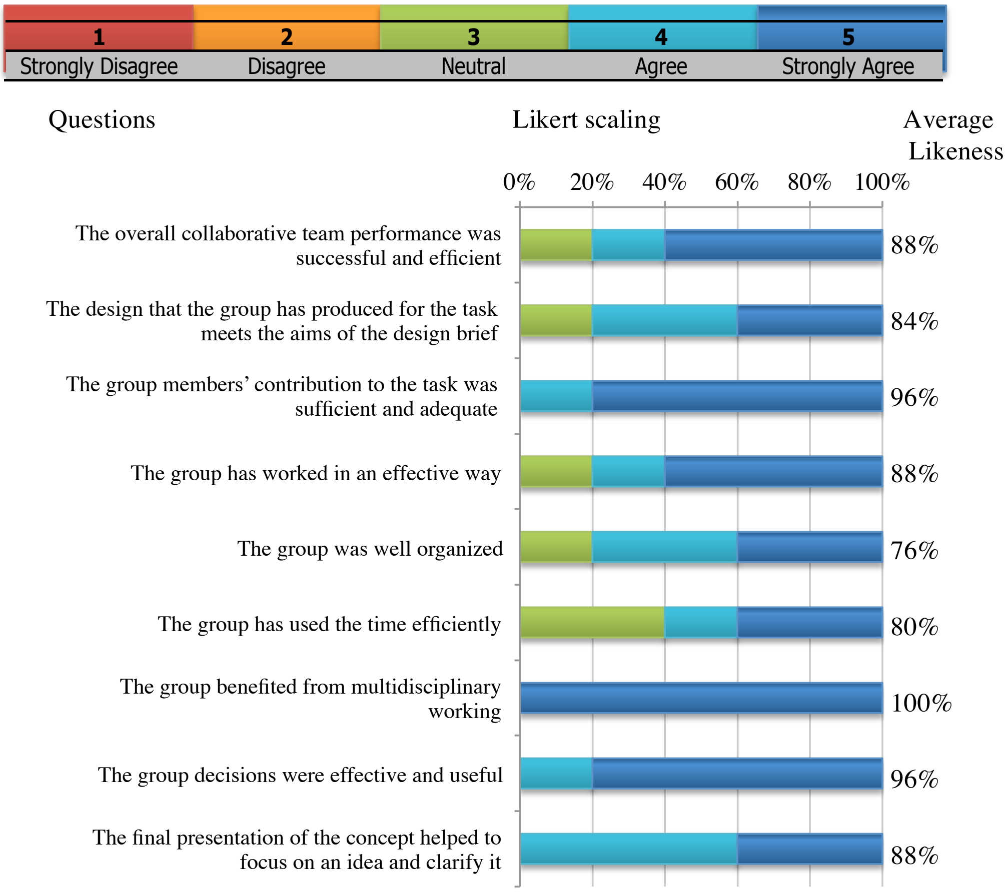


Figure 8.24 Preferred design medium

The second section of the questionnaires was formed into a Likert chart where the participants were asked to evaluate various aspects of the study according to their personal opinion, from the overall and group feedback, to the effectiveness of the conceptual design stages Protocol and up to user satisfaction regarding the developed design application for the M.S. PixelSense. The scale meter was the same with the second study and it depicted levels of likeness from 1 to 5 and from strongly disagree to strongly agree accordingly.

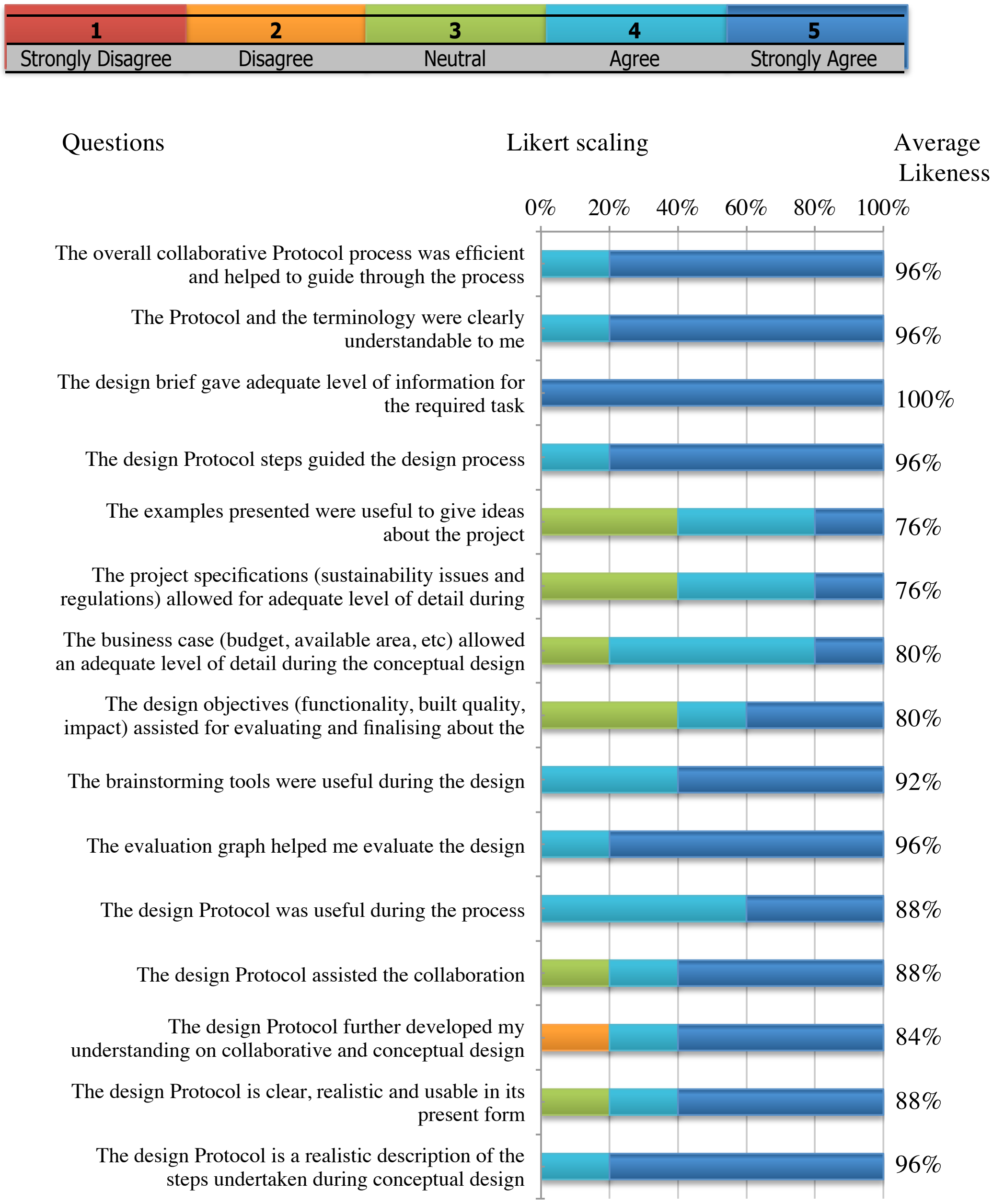
The first category of the questionnaires intended to provide feedback for the overall study process and the participants experience, as presented inTable 8.5. Participants were pleased with the study and the percentages of average likeness were quite high for all the different aspects that were asked. Their unanimous greatest positive feedback came from the acknowledgement that the group benefited from multidisciplinary working 100% of likeness), followed by the effectiveness of the group decisions (96%) and the efficient contribution from all the team members (96%). The lowest feedback was on group organisation (76% likeness); the team was happy with the teamwork but realised that they could have been even more effective during the study. Furthermore, they were happy with the end solution they produced and they believed it answered the design brief.

Table 8.5 Overall and group feedback Likert scale replies



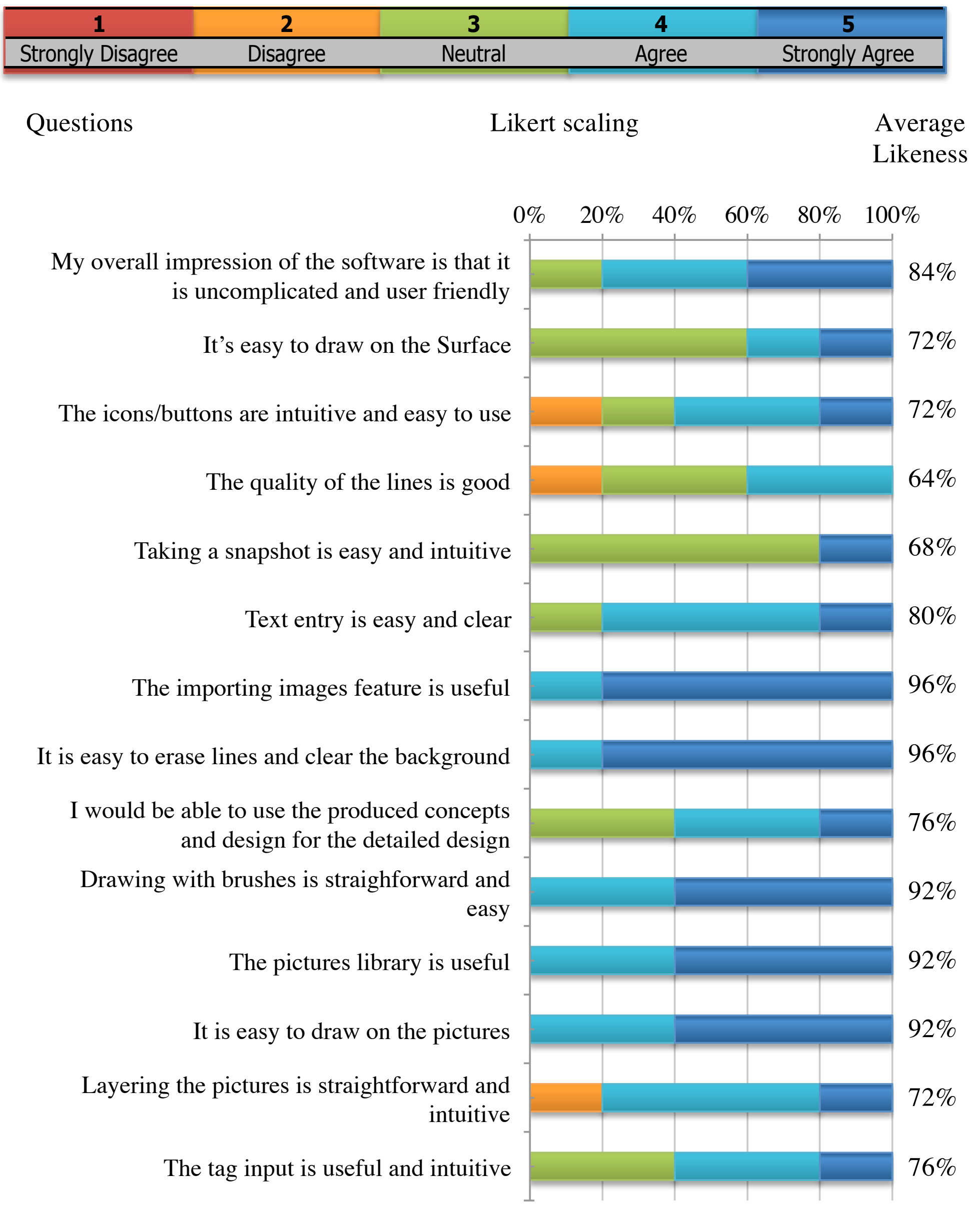
The second part of the questionnaire was focused on the use of the Conceptual Stages Design Protocol (Table 8.6). The average feedback was very strong and the participants found the overall collaborative protocol efficient, useful and helpful. The greatest levels of satisfaction (100% and 96% likeness) were observed regarding the details included in the design brief for the required task, the use of the evaluation tool for assessing the produced conceptual design, the steps that were guiding them during the process and the fact that the Protocol was a realistic description of reality for conceptual design. Very positive feedback was monitored in relation to the usefulness of various aspects like the brainstorming tools, the design Protocol in its current form and the assistance it provided for collaboration. The smaller percentages of likeness (76%) were related to the use of examples in the beginning of the process and the project specifications, the reason being that they were already looking for relevant examples themselves and that they did not consider that they had enough time to further adapt their project to strict sustainability specifications.

Table 8.6 Effectiveness of intended use of the Protocol Likert scale replies



The final part of the questionnaire was concentrated on user satisfaction of the M.S. PixelSense and the developed design application (Table 8.7). Similarly with the previous two sections, the participants were really satisfied with the TUI and they believed that it was uncomplicated and user-friendly, with very positive input regarding the ease of drawing and erasing lines, the significance of importing images and having an images library at hand. On the other hand, less positive feedback was provided for the intuitiveness of the menu, the ease of drawing on top of the surface due to its light sensitivity and the tag feature. Eventually, an average feedback was given for the snapshots option and the quality of produced lines.

Table 8.7 User satisfaction and application efficiency Likert scale replies



The questionnaires were succeeded by a final discussion with the participants, during which they reported that they were happy with the process and that they appreciated the multidisciplinary feedback and the restrictions due to budget and regulations' restrictions. Their impression on the TUI was very positive and they realised it "can be a great tool for having all the drawing tools on it", since it promoted instant communication and feedback. Furthermore, it became apparent that in normal circumstances the conceptual design would have taken longer to be involved while in the particular case, due to time limitations and the structure of the study, the ideas were flowing and were being revised quite fast, supported by cross analysis from the different disciplines.

They also suggested that they would have preferred to initiate their designs by utilising the TUI, to avoid losing time and allowing the simultaneous involvement of all the participants straight from the beginning of the study. Additionally, they considered that it would have been useful to be able to import excel spreadsheets on the TUI and get more information on cost while they were designing. At some point during the study, the team was separated in two smaller teams working on two separate laptops, and they commented that there was a lack of shared information during these points, even though they still kept discussing their various ideas. The participants also acknowledged that the education does not allow collaborative thinking, professional silos are cultivated during undergraduate studies and the gap grows when they go into practice.

8.3 Summary

The third study evaluated the CDSP and the updated design software. The whole duration of the study was closely monitored and the impact of the conceptual design stages Protocol and TUIs was examined. Furthermore, the participants provided feedback regarding the process and the design application and they were comprised out of last year students with a limited professional experience.

Regarding the application of the CDSP, it was apparent that they followed it quite close and they reached a final result through intense collaborative, conceptual, perceptual and physical activities. Communication was strong throughout the study and the discussions were flowing among the different disciplines, with a limited number of clashes and a more cooperative approach. Design was informed from the multidisciplinary feedback and the participants were reaching out to their colleagues for sharing opinions, information and ideas and getting feedback. As a result, the designs evolved constructively up to the beginning of detailed design.

The application of M.S. PixelSense for design purposes further supported the design process, thus providing the suitable environment for an uninterrupted engagement with the evolution of the conceptual stage. The participants were enthused with the capabilities of the TUI and they found potentials for its application within the construction industry for supporting a smoother and instant collaboration. Additionally, the comments were supported from the protocol analysis results that demonstrated the enhancement of design, collaborative and cognitive activities compared to the first stage when using physical design mediums. The TUI eventually promoted a smooth design and cognition continuum, thus encouraging the finalisation of their conceptual design.

The fact that the participants were students led to a more active approach to design and collaboration; the participants had no barriers during the collaboration that was open and unrestricted. Furthermore, they started designing from the very beginning of the study, which allowed ideas' exchange for a great number of potential design solutions within the multidisciplinary context.

9 Studies Comparison

This chapter aims to provide a comprehensive analysis and comparison of results from the three different studies. The first part of the chapter critically compares the findings from the three studies and categorises them according to the differences in components and the different in qualitative and quantitative results, with an overall feedback on the evolution of the design protocol and the software design tool. During the second part of the chapter, conclusions of the research are described and ideas for further development are presented.

9.1 Studies' Components

The three studies examined the effects of TUIs and collaborative design processes (the Predefined Conceptual Stages Protocol) to conceptual design. For accomplishing these studies a number of parameters had to be set, like the type of recruited participants, the different types of design mediums and digital media that were available during the studies, the features that were examined and the methods and processes of how this examination would take place.

It was essential to have a range of professionals representing the wide range of them that are typically engaged with built environment projects, including architects, surveyors, engineers and project managers, for the purpose of tackling the multidisciplinary focus of the research. Consequently, all three studies had representatives from all these professions, with the first two focusing on experienced professionals and the last one applying the same process and context with last year students/ new professionals. A number of results came from this aspect, with the most prominent one being the openness of new professionals to multidisciplinary collaboration and their ease to utilise and adapt to digital media for quicker design decisions. On the other hand, the professional team from the second study managed to adapt really well to the Conceptual Design Stages Protocol and make the most of their available time and means. Finally, the professional team of the first study was the one that showcased the weaknesses of the current paradigm of conceptual design, like miscommunications, professional silos and difficulties in making design decisions.

Furthermore, the type of different design mediums and digital media followed the purposes of the studies, which was to compare and contrast the current paradigm of design mediums and software utilised in the AEC industry for conceptual design and the proposed digital media and tangible interfaces. All three studies had two stages during the main brainstorming process, with the first one applying the current paradigm of mediums and means and the second stage utilising the TUIs. A key difference during the studies was the type of design application installed on the TUI, with the first study having a simple M.S. Drawing one, while studies two and three had a specifically developed application for the purposes of the particular research. This software provided a range of design tools to the participants, varying from drawing and deleting lines to importing pictures, finding resources online and taking notes and snapshots of their designs. The version utilised during the second study had some faults in the software and, as a result, an updated version had to be used for study three. No matter the installed version of software, it still was suitable for making comparisons between the two different design stages and it provided valuable results.

9.2 Studies' Comparison

The research question was focused at investigating conceptual design stages within the AEC industry and explaining through literature review and through studies the current paradigm and its problems. The acknowledgment of the knowledge gap in AEC industry between pre-BIM stages and detailed design, led to further investigations for achieving a smooth continuum from conceptual stages to detailed design through multidisciplinary and ICT assisted collaboration. Therefore, it was essential to record the activities continuum for all three studies and compare the processes with and without the application of the Conceptual Design Stages Protocol and with and without the application of ICT means.

9.2.1 Activities' Mapping Comparison and Benchmarking

The design progression patterns of the three studies were critically compared and the most important conclusions included the evolution of the design process and the faster progression of the feasibility stage when using the pre-defined design protocol. The data from the studies were compared using activities mapping, for understanding the consecutive phases of design, (Austin, Steele et al. 2001; Macmillan, Steele et al. 2001). The activities are mapped according to succession and duration based on the steps described by the Conceptual Design Stages Protocol. The activities' gradients were represented and the average design process of all three studies was compared and the summary of all three design progressions can be observed in Figure 9.1.

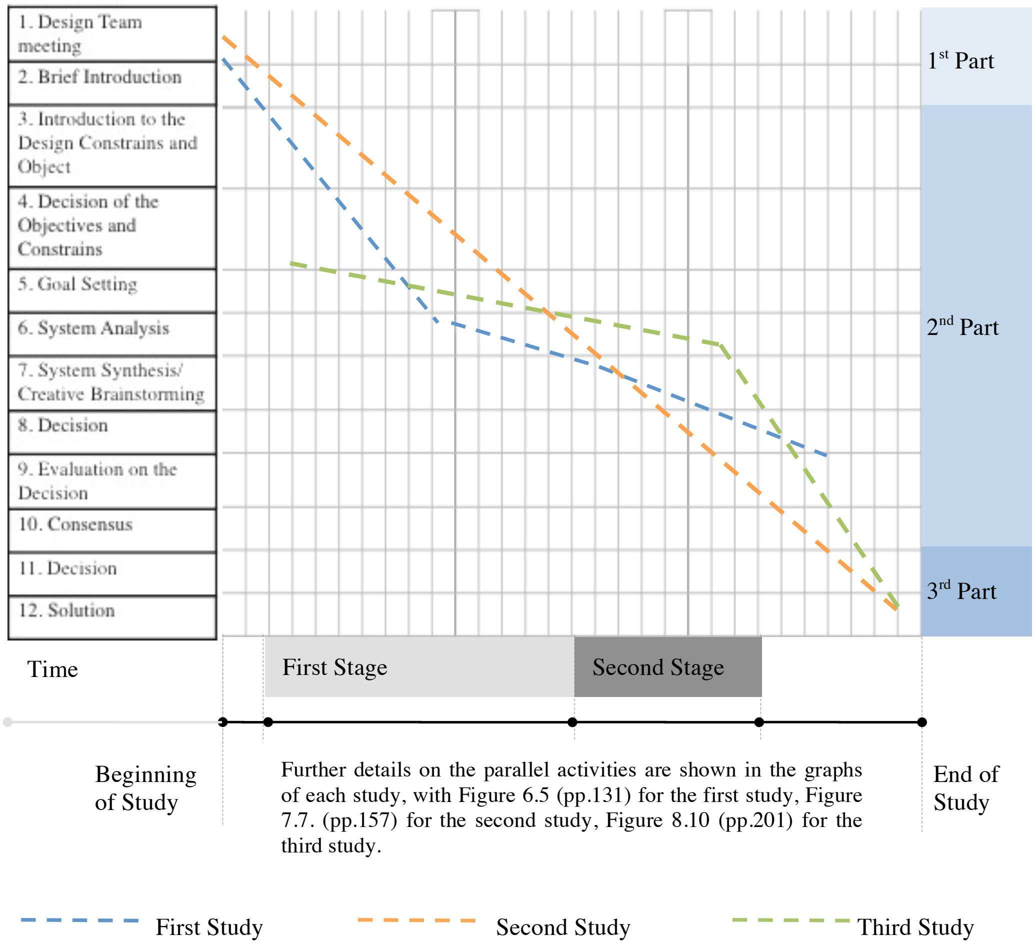


Figure 9.1 The design activities progression during the three studies

The first study monitored the current paradigm of conceptual design within a multidisciplinary team from the moment a team is handed a design brief. Furthermore, the participants were comprised out of professionals, there was no interference from the moderator regarding their process and the end result of their conceptual activities progression was fragmented. The particular team faced obstacles from the start due to the unwillingness of participants to collaborate with different disciplines while they stated that this work should be completed only by architects. Soon after though, they had some discussions on the objectives and constraints of the project, still without taking specific decisions about them. The process was slow overall, with no particular direction. The second stage of that study focused on the continuation of brainstorming by utilising the TUI. Commercial design software was available on the TUI and quite intense design brainstorming occurred during that stage. However, the process got stagnated due to lack of particular focus from the previous stage, participants were not that willing to collaborate and the team did not find a final solution through a team consensus.

On the other hand, the Conceptual Design Stages Protocol was applied during the second study. In this case, the team was comprised again from professionals and the activities progression showcased a very smooth succession. The participants were discussing the key issues of the project from the beginning of the first stage, taking decisions on them and moving to the next steps. Iterations between the steps were occurring but they were assisting at developing the conceptual design. For the second stage of this study, the participants were provided with specifically designed software for conceptual stages applied on the TUI. The design activities were intense and the maturity of the developed ideas evolved faster than in the first stage. The whole design process had a smooth continuum and the team eventually reached a design solution consensus.

Similar process was observed during the third study as well, even though in this case the participants were last year students. The last team did not spend time deciding on constraints and objectives, they rather focused on what was given on the brief and according to that they immediately started brainstorming on the conceptual design. The design application was also available on the TUI and it allowed a smooth continuation of their concepts development, thus reaching a design consensus by the end of the study. The third study had one more difference with the previous ones, regarding the different aspects that were considered within the duration of the study. Their focus was not holistic like the second study, thus their solutions were mostly focused on design and functionality, impact of the building, and less on construction and operation. A reason for that is the limited experience of the participants to make the relevant estimations of these aspects and also the slower undertaking of the study compared to more advanced and experienced participants.

During the second and third study, the application of the Conceptual Design Stages Protocol assisted the design process since it kept the participants focused on the design task steps and allowed the multidisciplinary collaboration since the design brief specifications and consequent decisions on it were requiring the consensus of all disciplines. Most importantly, it kept the participants on track regarding their own progress and they were able to self-manage the development of their ideas. The clarification of the initial decisions on project's objectives promoted the design progress since it allowed easier evaluation of the produced concepts against these objectives. The last two teams were able to work efficiently and develop their conceptual designs that reflected all the discussed topics and design briefs and also they achieved multidisciplinary agreement on the produced concepts. Furthermore, their actions were enhanced with the application of the design software on the TUI. Users' activities showcased creative and unexpected interactions with the physical means of exploring ideas, hence leading to a merging of physical and digital worlds that further promoted a vibrant collaborative design process with more extensive interactions between the participants.

Eventually as presented in Figure 9.1, the results from the application of the CDSP in the second and third study would consist the benchmarks for experienced and inexperienced users accordingly. The results from the second study present the application of the CDSP from senior professionals that tend to analyse the project requirements in greater detail. On the other hand, the progression showcased during the third study would consist the benchmark for inexperienced users that tend to send greater amount of time designing and discussing design solutions.

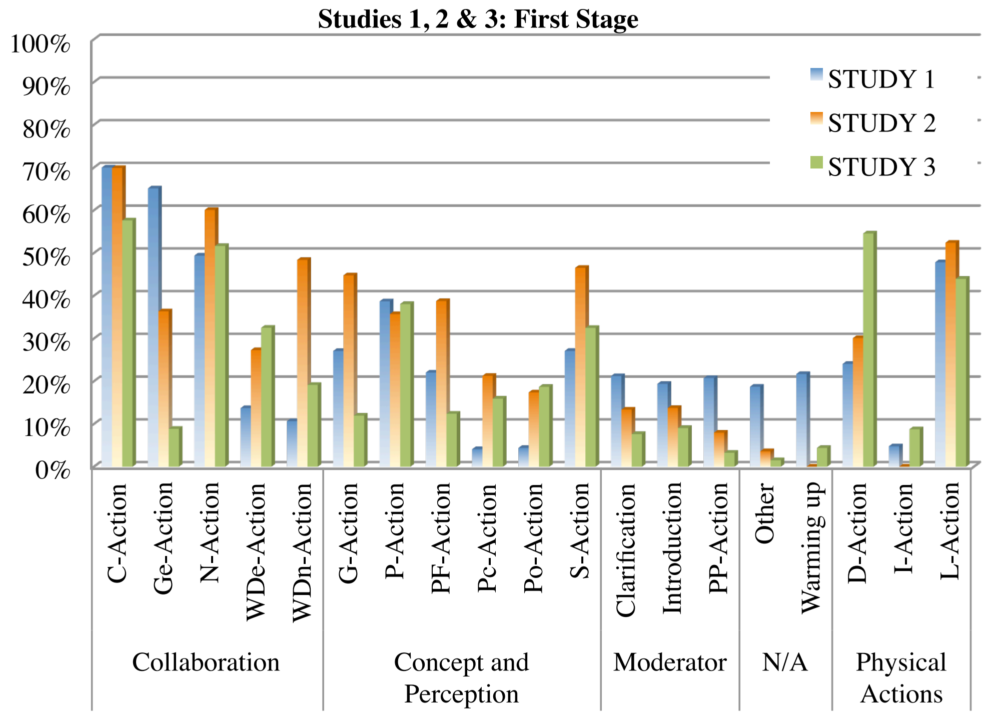
All three studies were compared in greater detail by utilising protocol analysis (Gero, Mc Neill 1998; Suwa, Purcell et al. 1998), for identifying the different types of actions during these stages. The actions' categorisation assisted in understanding the collaborative and cognitive processes and their relation to the Conceptual Design Stages Protocol and the utilised physical or digital design means. The actions were grouped in five different types to accommodate the research focus and this process was applied for all three studies for being able to comprehend the divergences among them.

9.2.1.1 Conceptual Design Stages Protocol Outcome according to Protocol Analysis and Benchmarking

Regarding the comparison of the processes that the teams followed in three studies, all of them had been monitored to incorporate strong collaborative actions, with the most prominent one being the second and third study where the collaboration was accompanied with intense negotiations and decisions on new and existing features, an aspect that was substantially lacking in the first study, as illustrated in Figure 9.2. Furthermore, the percentages of conceptual and perceptual activities were once again noteworthy for study two followed by study three, a fact that reflects the robust brainstorming, the extensive focus on comparing and organising elements and the clear goals that were set for the project evolution.

Once again, the perceptual and conceptual activities of the first study were extensive but mostly focused on brainstorming and developing new features, without having the relevant decision making for promoting the task. Therefore, the application of the Conceptual Design Stages Protocol in study two and three demonstrated satisfactory results regarding collaborative, conceptual and perceptual activities. The best example of applying the Conceptual Design Stages Protocol was study two where the team was comprised out of professionals. Finally, the second study had the top percentages in most action categories. Study three still managed to present really good results, therefore further supporting the application of Conceptual Design Stages Protocol, even though the weaknesses due to the type of participants.

Physical actions were supporting the conceptual and perceptual ones, and during study three the greatest duration of drawing occurred, followed by study two, while the least drawing happened during study one. The physical activity of inspecting the design brief, sketches, plans and layouts had a similar duration in all studies. Moderator's activities were quite prominent during the same study as well, for clarification and guidance to the participants. On the other hand, studies two and three did not require much interference from the moderator and the design process was smooth.



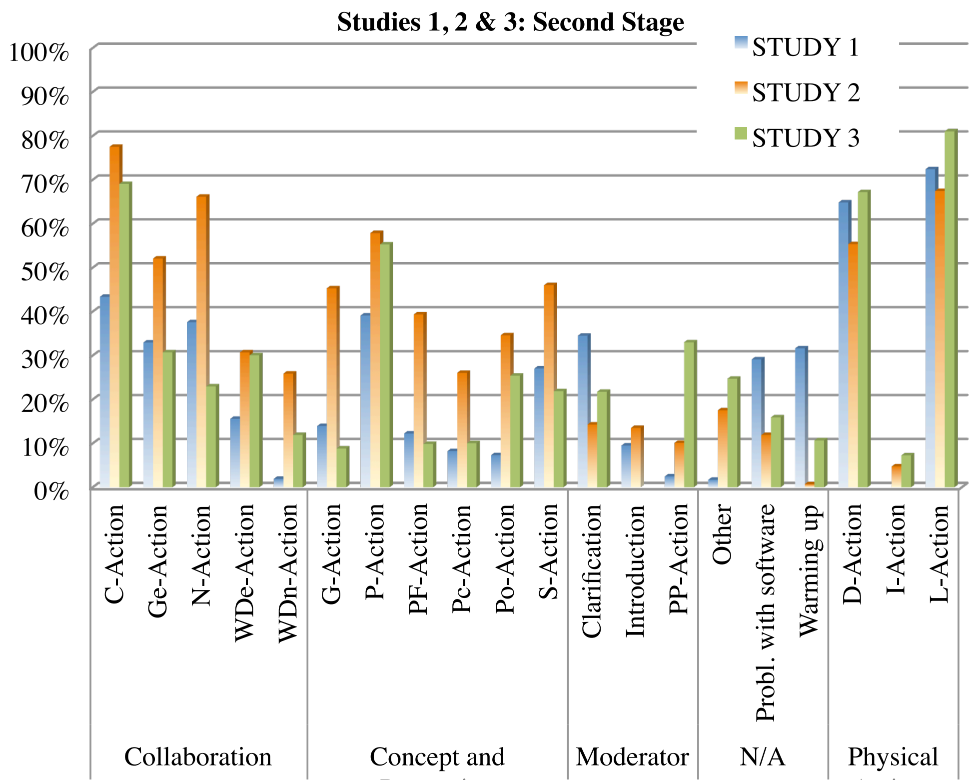


Figure 9.2 Comparing actions' duration during the first and second stage of all three studies

9.2.1.2 Influence of Technology and TUIs according to Protocol Analysis

The second stage from all three studies shares a similar characteristic regarding the smaller gap between the percentages of the duration of an action and its number of segments in the study (Figure 9.2). Consequently, the tangible nature of the digital means allowed an intuitive design approach, with a greater flexibility in expressing their concepts both verbally and physically, thus promoting faster transition between concepts and representations, enhanced collaboration among the participants and faster evolution of ideas. During the second stage, the moderator's action of promoting and supporting the process was also quite prominent during the third study, in contrast to the previous ones. The reason being that the participants were not experienced enough to follow closely a process and that they posed less barriers to guidance. On the contrary, during the second stage the team followed the process but it was more demanding for the moderator to manage their staying on track due to the strong professional silos managing the process.

The first two studies had an additional third part where the final idea was presented or in case of no design finalisation and eventual discussion took place. During the third study though, the third part was focused on transferring the design finalisation into BIM software and initiating the first stages of detailed design. Consequently, the duration of the third part of the studies was differentiated among all three, with the greatest duration during the third study, **highlighting the application of the CDSP as a 'warm-up' for transferring the design decisions to BIM.**

9.2.2 Segments' Duration and Comparison for the Three Studies

The monitored activities were being parallel in all studies and a number of graphs aim to illustrate the relation between actions and segments for the whole duration of each study, as depicted in Figure 9.3, Figure 9.4 and Figure 9.5. All three graphs share some common characteristics, some peaks in the duration of certain actions, like collaboration, inspecting elements, focusing on new and developing design features and brainstorming. Although all three studies had in common those peaks in the graphs, considerable variations in other actions distinguished the plotted results. For a start, the first study had the lowest workflow driver and the lowest attention on comparing and organising design elements, followed by the third study, with the top results observed in the second one. Although the previous results, study three has the greatest time percentage for decisions on developing features, a fact that reflects the greatest time percentage spent designing and sketching during the same study. Eventually, the drawing activity was the lowest in the first study.

Nonetheless, study three presented lower percentages of gestures when collaborating, which resonates with the type of participants since the students were more reluctant and courteous during the collaboration, with the other two studies having a more assertive communication among the participants. Furthermore, the third study presented lower percentage in the number of segments spent for focusing on new and developing features while study one showcased lower time percentage spent on the same activity. This means that the third team was focusing for longer periods of time discussing potential ideas, while the first team had a more fragmented focus while developing their ideas. These results shed additional light in the difficulties faced during the first study and also illustrate the accomplishment of the other two studies, with the best example being of study two where the team was comprised out of professionals.

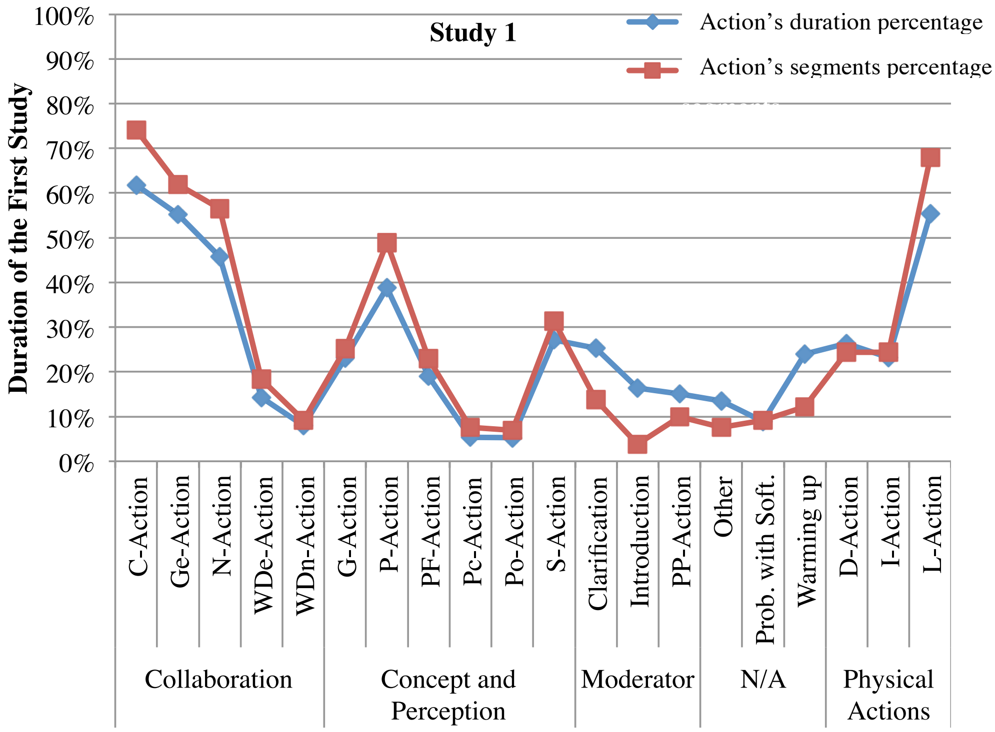


Figure 9.3 First study, comparison of actions' duration and number of segments

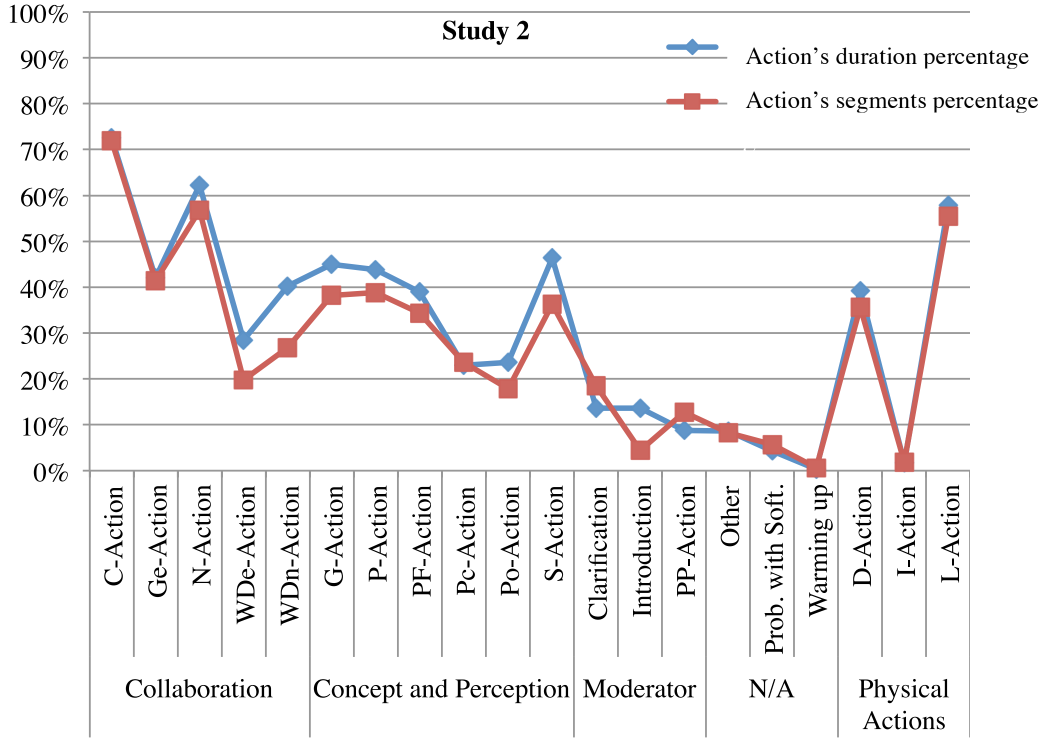


Figure 9.4 Second study, comparison of actions' duration and number of segments

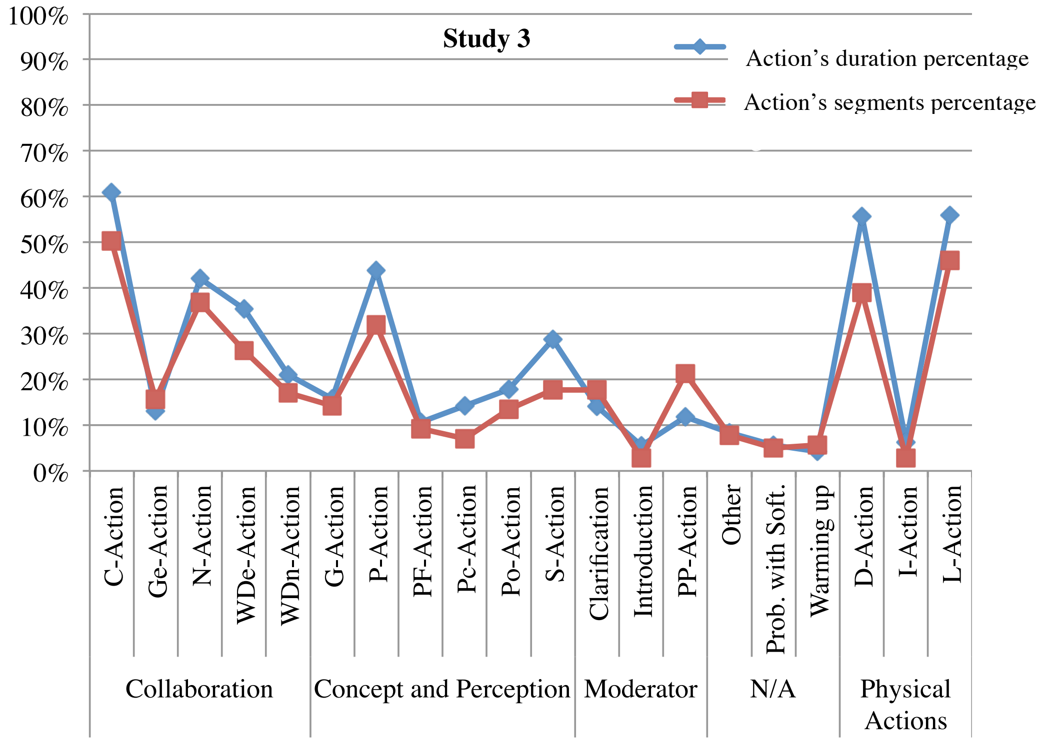


Figure 9.5 Third study, comparison of actions' duration and number of segments

9.2.3 Participants' Feedback for the Three Studies

9.2.3.1 Feedback on the Conceptual Design Stages Protocol

Discussions at the end of each study between the participants and the moderator demonstrated in greater detail the teams ideas and opinions on the design process and further supported the arguments for multidisciplinary and computer mediated collaboration. To begin with, all team were pleased with the multidisciplinary design, even though they reported different comments about it. The first team commented that they considered the process productive and they felt that the interdisciplinary approach widened their vision. On the other hand, the designers in this team feared that their creativity was restricted due to the input of the other disciplines, while in the beginning of the first study the project manager had commented on the suitability of the professional silos for each design stage.

The second team members reported that they would have preferred to work for a longer duration and apply the Conceptual Design Stages Protocol for a longer period of time. They also acknowledged the importance of multidisciplinary work and they recognised that for the available time they managed to produce a very good result that achieved team consensus. On the other hand though, the professional silos were quite strong in this case as well and it required hard work on the collaboration and ideas' exchange aspects. The third team gave the most positive feedback on the multidisciplinary work and the Conceptual Design Stages Protocol, were enthused with the ideas' exchange and realised that it was of great assistance during the process, even though they would have preferred to work for a longer duration.

9.2.3.2 Feedback on the Technology and the TUI

Regarding the application of the digital media during the second stage of the studies, the first team felt intimidated by the TUI and experienced technical problems; they did recognise the potentials though and suggested ideas to improve it. Similar results were monitored from the replies of the second team, even though the specifically developed design application assisted in the design process and it was uncomplicated and user friendly. The third team learned quite easily how to use the design application and they appreciated the potentials of such a tool for promoting communication within design teams. Eventually, both the second and the third team recognised that the process moved fast and they achieved quite advanced results for their available time, due to the Conceptual Design Stages Protocol application and the digital media. TUI was vital since due to the proximity of the medium and the ease of use, it managed to focus all the participants around the large tangible drawing surface and on top of the developing sketches, thus promoting discussions and communication on ideas and concepts.

10 Conclusions and Future Research

10.1 Limitations during the Research

A certain number of limitations were observed during the research and they were focused on various aspects of the studies. First of all, the duration of the stages among all studies presented that the first stage, where the participants were asked to use the current paradigm of design mediums, was lasting approximately for an hour and twenty minutes. On the other hand, the second stage with the use of the M.S. PixelSense had an approximate duration of forty minutes. The reason for this difference was that the first stage was following the introduction of the design brief and the project and sufficient time was required for the teams' formation, which could be a cumbersome task considering the different participating professional silos and personalities. Since the results from the first study showed that some participants could feel intimidated with the introduction of a computational design application, it was avoided adding an additional stressful parameter to an already strenuous process of team building. An additional limitation was the computer bugs on the developed design software that was interrupting the smooth design process. Once again, it was a recognised difficulty as it was acknowledged during the protocol analysis and it was partially tackled along the development of the design application. Furthermore, these difficulties and bugs provided sufficient input to improve the application between study 2 and study 3.

It was also acknowledged that the studies were human oriented and their number was limited due to research time constrains. Therefore, the focus of the studies was quite deep, on the human aspect of collaboration and the application of the developed tools (CDSP and the computational design tool). What is more, the experience of the participants was slightly differentiated between the first and second study, with one extra senior professional participating in the second study. On the other hand, the third study included last year students with limited professional experience for the purpose to highlight the lack of professional silos during the studies.

The studies involved laboratory based observations over time-limited design sessions. This fact did not affect though the design brief scale, with a number of requirements being requested for the end project. Moreover, it was an acknowledged aspect of the research; hence, the in vivo information coming from interviews and design teams' shadowing provided feedback for the in vitro simulations of the studies.

10.2 *Objectives of the Research*

A mixed methods research approach was applied during the thesis for allowing flexibility to adapt according to the research objectives. Furthermore, inductive approach was the method for identifying the gap in knowledge and research hypothesis through an extensive literature review and qualitative analysis of interviews and teams' shadowing. Deductive methods were employed in parallel for conducting three structured studies and the collected data were analysed with descriptive statistics. What is more, a highly iterative method was followed for conducting the studies and action research was applied to input the collected data coming from each study into the next one. Eventually, grounded theory was applied both for analysing the macroscopic data of the studies and for deriving the conclusions of the research.

The research question and aim that was set in the beginning of the thesis is:

With a focus in the AEC industry, can computer mediation assist and create an environment for conceptual collaborative design? Furthermore, can we support this process with a design protocol with fixed stages for a more efficient and effective conceptual design?

According to the presented research, the findings are that computer mediation can assist and create an enabling environment for collaborative design during concept and pre-BIM stages with a computational design tool having been developed and tested accordingly. Most importantly, the concept design stages can be effectively and efficiently supported with the application of a fixed steps design process as investigated, developed and applied with the Conceptual Stages Design Protocol during tests with multidisciplinary design teams, thus achieving a smooth integration of concept stage with the later BIM stages.

Each objective is further summarised accordingly:

10.2.1 Objective 1

- **Undertake a review of the current paradigm of conceptual collaborative design in the AEC industry.**

An extensive literature review was conducted that was related to the current paradigm in AEC industry, especially BIM and multidisciplinary working, and conceptual and collaborative design assisted through computer mediation. The review followed an inductive approach method and the developed theories were tested in the following chapters. These theories were focusing on increased effort during the early design stages as a prerequisite for effective overall design and construction stages (Sinclair 2012; Egan 2008; Hsu, Liu 2000; Wang, Shen et al. 2002) and for smoothly bridging conceptual ideas generation and advanced design stages. The proposed approaches for achieving this leap included multi-party agreement with early involvement of the stakeholders and designers (Harty, Laing 2011; Philp 2012; Lockley 2011), and Information and Augmented Reality Technologies implementation for a smooth continuum with BIM processes (Horváth, Vroom 2015; Schweikardt, Gross 2000; Dourish, Bell, 2007; McCall, Bennett et al.1990). Consequently, the development of a Conceptual Design Stages Protocol was suggested, which would encompass aspects enabling multidisciplinary collaboration, advanced comprehensiveness and informed decision-making. An additional aspect for supporting this Protocol included the development of a computational design tool for promoting concept design and integration with BIM.

10.2.2 Objective 2

- **Establish and optimise a Conceptual Design Stages Protocol for collaboration during the early and conceptual design stages using digital design and collaborative tools.**

The second aim focused on thoroughly investigating the methods and processes for conceptual design both from the AEC industry and from other relevant disciplines like engineering and design, as summarised in Appendix A. A Conceptual Design Stages Protocol was developed for guiding design teams during conceptual design stages. The Protocol incorporated structured steps with integrated regular points of decisions and design iterations that would assist to either take the process forward or to go back, redesign and reconsider. This Conceptual Design Stages Protocol was influenced from relevant processes already applied within design and engineering, like previous research from Schön (1991), Cross (2008), Pahl and Beitz (1988). It also clearly extended design processes within the AEC industry (RIBA Plan of Work 2013; PAS 1192-2:2013; BS 7000: Part 4) and it was developed as a pre-BIM process.

As it was further analysed in chapter 3 and illustrated in Figure 3.6 in page 57, the **Conceptual Design Stages Protocol** is highly adaptable and it represents a collaborative design process that could be applied at any point within the different stages of design. **Importantly, the decision points along the process reflect the shared views**

and agreements among the participants regarding the project. These decisions consist the small milestones within a project collaboration management where the informed consensus between the different disciplines is achieved. Additionally, the type of participants could further adapt according to the type of procurement utilised for a project. The duration of this process and its milestones are not restricted but it could be modified according to the requirements of a project. Regarding the application of the process, it could be facilitated by design, collaboration or project managers and it could easily be integrated within an on going or a new project. Further collected qualitative data that are presented in chapter 5 regarding interviews with AEC professionals with long experience in the sector and shadowing of design and construction teams, further emphasise the problems occurring during design collaborations and the importance of a process like the **Conceptual Design Stages Protocol**.

Additionally, a **computer mediated environment (Tangible User Interface) was employed to be facilitator for collaborative design,** thus helping multidisciplinary professionals work together efficiently and effectively by supporting ideation processes. A computational design tool applicable to Tangible User Interfaces was developed and the development brief is presented in **Appendix B**. The purpose to create an augmented reality environment that would further support collaborative design and extend relevant research in the field, from the Electronic Cocktail Napkin (Gross 1996), to more recent multi sensory input (Kim, Maher 2008; Zhen, Blagojevic et al.2013). Different sensory modalities were integrated that reflected the physical design actions and allowed the cyclic and dialectic process of drawing and sketching through multiple users operations. Non-intrusive interface and menu options promoted augmented operations, like importing pictures from libraries, picking colours, drawing on layers and taking snapshots, thus making use of a haptic experience for design ideation, the importance of which for design ideation was stressed by Pallasmaa (2009). Eventually, the developed computational design tool aimed at complementing the human capabilities during multidisciplinary conceptual design.

10.2.3 Objective 3

- **Facilitate and test both the current paradigm of conceptual design and the proposed Conceptual Design Stages Protocol, and undertake a critical comparison between the two.**

The third objective includes a number of subtopics that were analysed in different of chapters and it was subdivided into the following tasks:

10.2.3.1 Objective 3a.

a. Review relevant methodologies for investigating design processes and determine the methods to be applied during the studies.

The methodology for researching collaborative and conceptual design processes and computer mediation during concept design stages included testing in three different studies the current paradigm of conceptual design and the proposed Conceptual Design Stages Protocol and the computational design tool, which evidently extended previous research on collaborative design (Ben Rajeb, Lecourtois et al. 2010; Badke-Schaub and Frankenberger 2002; Dorta, Pérez et al. 2008). All three studies were video recorded, they were simulating the process a team follows after handing a design brief until the initial concepts are developed and they shared the same structure, composed out of three parts. The first part was the introduction to the study and the handing of the design brief to the participants. The second part, where the actual brainstorming was taking place, was divided into two stages; during the first stage the participants were asked to involve their ideas using traditional design mediums and in the second stage they were asked to use a Tangible User Interface. The third part of the studies contained the finalisation of the conceptual design, an end-discussion and questionnaires.

The analysis of the studies involved examining audio and video recordings of each study, and the answered questionnaires. Two different methods were applied for the analysis of the audio and video; the protocol analysis and the activities mapping. The first one is a macroscopic analysis for identifying participants problem solving and cognitive actions, identifying collaboration actions and monitor participants interactions with computer media and physical design mediums, a methodological approach first established from Gero and McNeill (1998) and further adapted from Gabriel and Maher (2002) and Gu, Kim et al. (2011). The second method allows mapping the evolution of the design process of the studies within time (Austin Steele et al. 2001). As a result, observations on the effectiveness of the intended use of the Conceptual Design Stages

Protocol and the impact of the computational design tool on conceptual design could be mapped and monitored.

10.2.3.2 Objective 3b.

b.	Investigate the problems currently faced during concept stages within the AEC industry through interviews and meetings' shadowing with senior AEC professionals to further support the research focus.

Face to face semi-structured interviews with eight senior AEC professionals from a range of disciplines and two design teams' shadowing provided in vivo feedback from the AEC industry on issues faced during collaborative conceptual design. The discussed topics during the interviews showed some shared emerging patterns. Working in professional silos and having separate solutions for the different type of professionals was one of them. Furthermore, issues with briefs' requirements concerned time limitations for developing concept ideas and budget restrictions. All of the interviewees stressed out the importance of a clear brief and communications among all involved parties and the significance of technology for designing, calculating and managing a project and the potentials for the application of BIM during a project. The feedback from shadowing two large multidisciplinary teams could be summarised into the further separation of the teams into smaller ones, which were discussing interrelated topics. In both cases, the project manager would bring together the smaller teams, would stress out the time constraints and the different tasks and would also keep the team focused and prompt ideas generation for the different issues of the project. Two major common problems were observed among all interviews and shadowing processes, with the first one being the changes on the brief coming from the clients, due to misinformation and lack of feedback and input among stakeholders, thus leading to a disorganised process. The second problem was the fragmentation of the AEC industry that forces professionals to work in silos with each type being employed at certain points within design and construction, hence not allowing effective communication and prediction and avoidance of potential problems.

10.2.3.3 Objective 3c.

c.	Undertake three studies during which the current paradigm of concept stages, the proposed Conceptual Design Stages Protocol and computational design tool are tested.

Three different studies were employed for observing and monitoring teams' interactions during concept design. The first study was an exploratory one and it followed a team of multidisciplinary AEC professionals during the conceptual design of a building. The team used physical design mediums and a Tangible User Interface with off-the-shelf installed commercial design software. The purpose of this study was to understand the steps undertaken by a multidisciplinary team during concept stage and the capabilities and potentials of augmented technology. The results showcased a range of problems both with the process and the technology and they dictated the development of a Conceptual Design Stages Protocol and of a specific computational design tool for the Tangible User Interface.

The second study followed a team of fully qualified professionals that applied the Conceptual Design Stages Protocol and the developed computational design tool; hence, this study provided an initial feedback on the developed tools. The activities taking place during conceptual design were monitored and the impact of the Conceptual Design Stages Protocol and the computational design tool during the study were examined.

Similarly, the third study supported an evaluation of the Conceptual Design Stages Protocol and the developed computational design tool. The participants were last year students of the AEC industry for the purpose of monitoring the professional silos development and how communication flows are affected by multidisciplinary collaboration. An additional difference of this study to the previous one was that after the completion of the conceptual design the participants were asked to transfer their decisions into BIM.

10.2.3.4 Objective 3d.

d.	Compare and contract the results from the studies regarding the processes; the current paradigm and the Conceptual Design Stages Protocol.

All of the three studies showcased collaborative actions, with the most prominent ones observed in the second the third study, where the Conceptual Design Stages Protocol and the developed computational design tool were applied. The conceptual and perceptual actions of the first study were not followed by decisions on aspects of the project, thus leading to a disorganised approach and a lack of a final conceptual solution. What is more, physical actions of drawing and sketching that promote ideation were equally strong in studies two and three while in study one sketching was limited.

Regarding the activities mapping among the three studies and the steps the teams followed, it became apparent that the first study was slow, it had a fragmented conceptual design process and it also faced obstacles due to the multidisciplinary approach. On the other hand, the second study had a smooth succession of steps and it followed the stages of the Conceptual Design Stages Protocol, while the multidisciplinary aspect enhanced the conceptual design. Similarly, the third team followed a smooth process and collaboration, professional silos disappeared among them and they successfully tackled the design brief up to the point of bringing their ideas into Revit.

Overall, the conceptual and perceptual activities were enhanced in the second and third studies thus reflecting a robust brainstorming process and an extensive focus on comparing and organising elements of the project. The studies extended previous research on conceptual design processes (MacMillan, Steel et al. 2001; Pahl and Beitz 1995; Archer 1984) by applying the Conceptual Design Stages Protocol within multidisciplinary collaborative design teams and by making use of Tangible User Interfaces for supporting design ideation.

10.2.3.5 Objective 3e.

e. Compare and contrast the application of the current paradigm of design mediums and the Tangible User Interfaces for conceptual brainstorming.

The tangible nature of the digital means allowed an intuitive design approach in all three studies, with a greater flexibility in verbal and physical concepts externalisation occurring when the participants were utilising the developed computational design tool, during the second and third study. The ease of expressing teams' ideas promoted faster transition between concepts and representations and it led to enhanced collaboration among the participants and faster evolution of ideas. The studies extended previous research on the impact of Tangible User Interfaces during collaborative design (Kim, Maher 2008) with the application of these Interfaces within multidisciplinary teams and by making use of an organised approach as defined by the Conceptual Design Stages Protocol.

10.3 Research Contribution

On the whole, this research has the potential to improve the final design solutions for buildings, by making it possible for multidisciplinary teams to work collaboratively and to involve stakeholders more effectively at the early stages of the design process. The maps of design progression provided insights in the nature of multidisciplinary design process and showed the effectiveness of the Conceptual Design Stages Protocol. Furthermore, even though differences might appear between the teams, depending on working environments and on social aspects of collaboration, the design activities and processes are ubiquitous, thus further reinforcing the application of the CDSP as an adaptable process applicable not only to the feasibility stages but at different stages where design collaboration is a prerequisite. This research also suggests a new role for design teams, the moderator of the Conceptual Design Stages Protocol, or else the "collaboration" manager. The purpose of this role is to further adapt the CDSP to the AEC industry and to effectively tackle problems with collaboration straight from the beginning of a project.

BIM and the technology evolution regarding creating, sharing and collecting relevant information for the AEC industry projects is shifting the focus to effective and efficient collaboration among the different professional viewpoints. The reason being that a merged design and collaboration management encapsulates the potential for enhanced quantitative and qualitative outcomes for greater functionality and perspective to the project together with better investigated, wider based and well-reasoned design solutions. Integrated project delivery further supports the holistic approach to design projects and decision making for waste avoidance. This collaborative working though could be achieved with a bridging among the different type of professionals and stakeholders for informative communication.

The research designed, applied and tested vigorously an organised design process coming from the Conceptual Design Stages Protocol, which was supported with a design-integrated approach to technology, and it managed to focus the participants, enhance multidisciplinary collaboration and communications, promote the ideation processes and lead to effective solution finding progressions. *The application of such a Protocol within the construction industry would have a very significant impact, not only to the design and construction of a project but particularly in relation to sustainability.* Unless sustainability issues are considered at the earliest design stage it is much harder to retro-fit them at a later stage due to the embodied energy. A collaborative design team working on a new project can have the relevant information to hand, but by using this Protocol they can start to see the effects of the decisions they take at an early stage, which hopefully would eventually lead to a more sustainable approach to the built environment. Eventually, the testing of a Conceptual Design Stages Protocol within the context of a multidisciplinary team using a visual ICT tangible interface is an original contribution to design research in itself.

10.4 Future Research

The Conceptual Design Stages Protocol intents to bridge pre-BIM stages with later and more complex detailed design development. As it was mentioned throughout the thesis, potentials for further development of the Protocol could incorporate developments regarding its functionality and application within the industry; some key recommendations include its smooth integration with the RIBA Plan of Works and its extension for the Life-Cycle of a project. Furthermore, building computational connections between the developed design application and the BIM platforms, in an uninterrupted way, could advance BIM adoption by avoiding losing focus of the design team between concept creation, detailed and construction designs.

10.4.1 Computational Version of the Conceptual Design Stages Protocol

An initial idea for further research is the development of a computational version of the Conceptual Design Stages Protocol as a pre-BIM software with fixed steps to guide design teams. This software would aim at shifting from the fragmentation of the industry to a holistic and collaborative approach and from the detachment of feasibility stages with the rest of the project to a smooth continuum of a project among the different design stages. The proposed software would incorporate the steps of the Protocol with suggestions during each of the step that are focused on generic and project specific aspects. The generic aspects include brainstorming methods for the design teams to investigate design solutions, design principles of “good design” and some generic standards. On the other hand, the project specific aspects are based on other examples of similar projects, considerations coming from different resources (requirements from the clients, requirements from the end-users), relevant specifications and British Standards.

10.4.2 Development of the Computational Design Tool as a BIM plug-in

Building uninterrupted computational connections between the developed computational design tool and the BIM platforms could advance BIM adoption by avoiding losing focus and data of the design team between concept creation, detailed and construction designs. This could be achieved by incorporating the development of the computational design tool as a plug-in for BIM. As it was demonstrated during the thesis and according to the feedback from the studies, the incorporation of different type of data allows a more inclusive way of discussing and deciding on developing ideas during concept design stages. What is more, the manual transferring of ideas from the M.S. PixelSense to paper and back to measured input to Revit resulted in losing not only valuable time but also the momentum of ideation. Therefore, finding an effective way to transfer the data from the feasibility stages to detailed design will further assist in the optimisation of the pre-BIM stages.

Managing the existing difficulties with computer bugs and improving the already developed 3D block design are some of the additional features suggested to be included in this plugin. Additionally, being able to import different types of files, like textual or numeric ones, and connecting them to developed ideas and features could further enhance the information of the feasibility stages.

10.4.3 Scanned data for Conceptual Design

Transferring scanned data of existing structures or sites to BIM, turning them into a mesh, (by utilising Autodesk Recap for example) and being able to utilise them in different ways is also one of the potentials of the computational design tool. An additional experimental approach would involve integrating scanned data within TUIs for conceptual stages design. Transferring the data and the 3D mesh to an updated design application could allow sketching and drawing on top of them, thus easier involvement of the design team participants. A connection with fabricating machinery like 3D printing or laser cutting could additionally enhance the ideation process and would promote a more effective presentation of the developed ideas.

10.4.4 Further ideas

Further research could also embark on the point of developing new areas of technology applications by implementing more advanced methods for Human-Computer Interaction, like advanced Augmented and Virtual Reality applications. Nowadays, technology is at a stage where barriers fro technology adoption are becoming less and less technical but more focused on social and perceptual issues. As a result, the application of augmented technology in the AEC industry, for the purpose of enabling users to interact with information coming from different types of resources (i.e. sketches, 3D drawings, BIM models, spreadsheets and regulations), could allow an immersive experience of projects. This experience could facilitate improved synchronous and asynchronous communications and enhanced collaborative information exchange within multidisciplinary participants by utilising Cloud-based platforms. A multi-device configuration for allowing users to interact with different types of information coming from different co-located or distant resources is an additional aspect for further improvement of the design application.

Eventually, the “thinking hand” as an instrument for ideation, communication and craftsmanship is at the core of sketching, drawing and eventually simulating and implementing Building Information Modelling. Furthermore, the technological advances enable simulations of the built environment projects, from the concept stages, which is the focus of this research, to the cost, constructability, and time and site organisation of the projects. However, there is the impossibility of mastering the diversity of technical languages and seeking the multiplicity of professional viewpoints from the early design stages can produce informed results that are less prone to errors and costly design iterations at later and more advanced stages. As Derrida mentions, “this also means that the construction of architecture will always remain labyrinthine. The issue is not to give up one point of view for the sake of another, which would be the only one and absolute, but to see a diversity of possible points of view” (Derrida 2006).

References

A

A. ELLIS, C., GIBBS, S.J. and REIN, G., 1991. Groupware: some issues and experiences. *Commun. ACM,* **3**4(1), pp. 39-58.

AALST, W.M.P. and HEE, K.M., 2002. *Workflow Management: Models, Methods, and Systems*. MIT Press edn. Cambridge MA.

ACHTEN, H., DE VRIES, B. and JESSURUN, J., 2000. DDDOOLZ. A Virtual Reality Sketch Tool for Early Design, *CAADRIA 2000 [Proceedings of the Fifth Conference on Computer Aided Architectural Design Research in Asia*] 2000, pp. 451-460.

ACS, Z.J., GROOT, H.L. and NIJKAMP, F.P., 2002. Knowledge, Innovation and Regional Development. In: Z.J. ACS, H.L. GROOT and F.P. NIJKAMP, eds, *The Emergence of the Knowledge Economy, Advances in Spatial Science*. Berlin: Springer-Verlag, pp. 1-14.

ADOBE CREATIVE CLOUD, Mobile Apps. Available: http://www.adobe.com/uk/creativecloud/catalog/mobile.html [02/04, 2015].

AIA, C.C., 2007-last update, Integrated Project Delivery: A Working Definition. Available: http://www.aia.org/groups/aia/documents/pdf/aiab083423.pdf [02/04, 2015].

ALIAKSEYEU, D., MARTENS, J. and RAUTERBERG, M., 2006. A computer support tool for the early stages of architectural design. *Interacting with Computers,* **1**8(4), pp. 528-555.

ANDERSON, N.R. and WEST, M.A., 1998. Measuring climate for work group innovation: development and validation of the team climate inventory. *Journal of Organisational Behavior,* **1**9(3), pp. 235-258.

AOUAD, G., LEE, A. and WU, S., 2006. *Constructing the Future*. Oxon, UK: Routledge.

ARAUJO, B., JORGE, J. and DUARTE, J., 2012. Combining Virtual Environments and Direct Manipulation for Architectural Modeling, *Digital Physicality - Proceedings of the 30th eCAADe Conference - Volume* 2 2012, pp. 419-428.

ARCHER, L.B., 1984. Systematic Method for Designers. In: N. CROSS, ed, *Developments in Design Methodology*. Chichester: John WIley & Sons, pp. 57-82.

ARIAS, E.G., 1995. Designing in a Design Community: Insights and Challenges, *Proceedings of DIS'95 Symposium on Designing Interactive Systems: Processes, Practices, Methods, & Technique*s 1995, pp. 259-263.

ASTROTH, J., 2008. Computer environments for GIS and CAD. *Encyclopaedia of GIS*. Springer, pp. 112-118.

AUSTIN, S., STEELE, J., MACMILLAN, S., KIRBY, P. and SPENCE, R., 2001. Mapping the conceptual design activity of interdisciplinary teams. *Design Studies,* **2**2(3), pp. 211-232.

AUTODESK, Sketchbook application. Available: https://itunes.apple.com/us/app/sketchbook-mobile/id327375467 [04/02, 2015].

AUTODESK 360. Available: https://itunes.apple.com/gb/app/autodesk-a360/id874184071?mt=8 [04/02, 2015].

B

BADKE-SCHAUB, P. and FRANKENBERGER, E., 2002. Analysing and modelling cooperative design by the critical situation method. *Travail Humain,* **6**5(4), pp. 293.

BALNAVES, M. and CAPUTI, P., 2001. *Introduction to Quantitative Research Methods: An Investigative Approach*. London: SAGE Publications.

BARTLE, R., 2003. *Designing virtual worlds,* New riders games.

BEALE, R., 2007. Supporting serendipity: Using ambient intelligence to augment user exploration for data mining and web browsing. *International Journal of Human-Computer Studies,* **6**5(5), pp. 421-433.

BECERIK-GERBER, B., DES, D. and KENT, D., Implementation of Integrated Project Delivery and Building Information Modeling on a Small Commercial Project. Available: http://i-lab.usc.edu/documents/Integrated%20Project%20Delivery%20and%20Building%20Information%20Modeling%20on%20a%20Small%20Commercial%20Project%202.pdf[2014].

BEN RAJEB, S., LECOURTOIS, C. and GUENA, F., 2010. Operations of Conception in Architectural Collaborative Design, *FUTURE CITIES: 28th eCAADe Conference Proceeding*s, 15-18 September 2010 2010, eCAADe, pp. 687-695.

BIM IN AUSTRALIA, December 2010. *Report on BIM/IPD Forums Held in October/November 2010*. Australian Institute of Architects, Autodesk, Consult Australia.

BIM TASK GROUP, 2012-last update, COBie UK 2012 [Homepage of HM Government, BIS], [Online]. Available: http://www.bimtaskgroup.org/cobie-uk-2012/2013].

BING, L., AKINTOYE, A., EDWARDS, P.J. and HARDCASTLE, C., 2005. The allocation of risk in PPP/PFI construction projects in the UK. *International Journal of Project Management,* 23(1), pp. 25-35.

BODEN, M., 1991. *The Creative Mind: Myths and Mechanisms*. New York: Basic Books.

BOTON, C., KUBICKI, S. and HALIN, G., 2013. Designing adapted visualisation for collaborative 4D applications. *Automation in Construction,* **3**6(0), pp. 152-167.

BOURNE, L., 2009. *Stakeholder relationship management*. Surrey: Gower.

BRAHAM, W.W., HALE, J.A., (eds) 2006, *Rethinking Technology: A Reader in Architectural Theory*. Taylor & Francis.

BRATTETEIG, T. and WAGNER, I., 2012. Spaces for participatory creativity. *CoDesign,* 8(2-3), pp. 105-126.

BS 1192:2007, January 2008. *Collaborative production of architectural, engineering and construction information. Code of practice.*

BS 7000-4:2013 *Design management systems. Guide to managing design in construction.* 2013. London, UK, BSI: British Standards Institution.

BUCCIARELLI, L.L., 1988. An ethnographic perspective on engineering design. *Design Studies,* 9(3), pp. 159-168.

BURRY, J. and BURRY, M., 2012. *The new Mathematics of Architecture.* London: Thames and Hudson Ltd.

BUSBY, J.S., 2001. Error and distributed cognition in design. *Design Studies,* **2**2(3), pp. 233-254.

BUTLER-BOWDON, T., 2006. Lateral Thinking. *50 Psychology Classics.* London: Nicholas Brealey Publishing, pp. 38-41.

C

CARPO, M., 2013. *The digital turn in architecture 1992-2012.* West Sussex, UK: Wiley.

CHANDRASEGARAN, S.K., RAMANI, K., SRIRAM, R.D., HORVÁTH, I., BERNARD, A., HARIK, R.F. and GAO, W., 2013. The evolution, challenges, and future of knowledge representation in product design systems. *Computer-Aided Design,* **4**5(2), pp. 204-228.

CHEN, C., ZHAO, G., YU, Y. and DENG, H., 2015. Multiple views system to support awareness for cooperative design. *Computer-Aided Design,* 63 (0). pp. 39-51.

CHENG, N.Y., 2003. Approaches to design collaboration research. *Automation in Construction,* 12(6), pp. 715-723.

CHESTNUT, H., 1965. *Systems Engineering Tools.* New York: John Wiley & Sons Inc.

CHUAN CHUA, K., QIN, Y., BLOCK, F., PHILLIPS, B., DIAMOND, J., EVANS, E.M., HORN, M.S. and SHEN, C., 2013. FloTree: a multi-touch interactive simulation of evolutionary processes, *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces* 2013, ACM, pp. 299-302.

CHURCHILL, E. and SNOWDON, D., 1998. Collaborative virtual environments: an introductory review of issues and systems. *Virtual Reality,* 3(1), pp. 3-15.

COBie Data Drops, Structure, users & examples. 2012. http://www.bimtaskgroup.org/wp-content/uploads/2012/03/COBie-data-drops-29.03.12.pdf edn. Cabinet Office, BIS, BIM, Ministry of Justice, ECS.

COMMISSION FOR ARCHITECTURE AND THE BUILT ENVIRONMENT (CABE), 2011-last update, More about monitoring design quality. Available: http://webarchive.nationalarchives.gov.uk/20110118095356/http:/www.cabe.org.uk/buildings/monitoring-design-quality/info [10/08, 2013].

COMMISSION FOR ARCHITECTURE AND THE BUILT ENVIRONMENT AND THE OFFICE OF GOVERNMENT COMMERCE, 2011. *Improving Standards of Design in the Procurement of Public Buildings*. 2013. http://webarchive.nationalarchives.gov.uk/20110118095356/http://www.cabe.org.uk/files/improving-standards-of-design-in-the-procurement-of-public-buildings.pdf: [03/15, 2014].

CONSTRUCTING EXCELLENCE LIMITED, 2004. *Procurement. http://www.constructingexcellence.org.uk/pdf/fact_sheet/procurement.pdf* edn. Constructing Excellence.

Construction (Design and Management) Regulations, The, 20072010-last update [Homepage of The National Archives], [Online]. Available: http://www.legislation.gov.uk/uksi/2007/320/contents/made [02/27, 2013].

CROSS, N., 2008. *Engineering Design Methods - Strategies for Product Design*. 4th Edition edn. West Sussex, England: John Wiley & Sons.

CROSS, N., 1999. Natural intelligence in design. *Design Studies,* 20(1), pp. 25-39.

CROSS, N. and CLAYBURN CROSS, A., 1995. Observations of teamwork and social processes in design. *Design Studies,* **16**(2), pp. 143-170.

CUREDALE, R., 2012. *Design Methods 1: 200 ways to apply design thinking*. Topanga, USA: Design Community College Inc.

CUTCLIFFE, J.R., 2000. Methodological issues in grounded theory. *Journal of advanced nursing,* 31(6), pp. 1476-1484.

D

DAENZER, W.F., 2002. *Systems Engineering*. Revision edn. Zurich: Industrielle Organisation Zürich.

DAINTY, A., MOORE, D. and MURRAY, M., 2006. *Communication in Construction*. Oxon: Taylor&Francis.

DARKE, J., 1979. The primary generator and the design process. *Design Studies,* 1(1), pp. 36-44.

DE BONO, E., 1990. *Six Thinking Hats*. London: Penguin.

DEBERNARD, D.M., 2008-last update, Beyond Collaboration—The Benefits of Integrated Project Delivery. Available: http://www.aia.org/akr/Resources/Documents/AIAP037286 [08, 2014].

DERKS, D., FISCHER, A.H. and BOS, A.E.R., 2008. The role of emotion in computer-mediated communication: A review. *Computers in Human Behavior,* 24(3), pp. 766-785.

DERRIDA, J., 2006. Architecture Where the desire may live. In: N. LEACH, ed, *Rethinking Architecture: a reader in cultural theory*. Oxon, UK: Routledge, pp. 319-323.

DÉTIENNE, F., MARTIN, G. and LAVIGNE, E., 2005. Viewpoints in co-design: a field study in concurrent engineering. *Design Studies,* 26(3), pp. 215-241.

DORTA, T., PÉREZ, E. and LESAGE, A., 2008. The ideation gap: hybrid tools, design flow and practice. *Design Studies,* 29(2), pp. 121-141.

DOURISH, P. and BELL, G., 2007. The infrastructure of experience and the experience of infrastructure: meaning and structure in everyday encounters with space. *Environment and Planning B: Planning and Design,* 34(3), pp. 414-430.

DUNBAR, K., 1995. How scientists really reason: scientific reasoning in real-world laboratories. In: R. J. STERNBERG & J. E. DAVIDSON eds., *The nature of insight*. Cambridge, MA: The MIT Press, pp.365-395.

E

EAGLESHAM, G., 1979. CAD: state of the art: 16 September 1978, London. Organized by TASS (Technical, Administrative and Supervisory Section) of the Amalgamated Union of Engineering Workers. *Computer-Aided Design,* **11**(2), pp. 85-91.

EAST, E.W., 2013-last update, Construction Operations Building Information Exchange (COBie) [Homepage of WBDG, National Institute of Building Sciences], [Online]. Available: http://www.wbdg.org/resources/cobie.php [03/02, 2013].

EASTMAN, C.M., 1991. The evolution of CAD: Integrating multiple representations. *Building and Environment,* **2**6(1), pp. 17-23.

EGAN, J., 2008. *Accelerating Change*. Strategic Forum for Construction.

EGAN, J., 1998. *Rethinking Construction, The Report of the Construction Task Force*. UK: HMSO.

EGGLESTON, B., 2008. *Liquidated Damages and Extensions of Time: In Construction Contracts*. 3rd Edition edn. Oxford: Wiley-Blackwell.

EMMIT, S. and YEOMANS, D.T., 2008. *Specifyiing Buildings, a Design Management Perspective*. 2nd edn. Oxford: Butterworth-Heinemann, Elsevier.

EMMITT, S. and GORSE, C., 2003. *Construction Communication*. Cornwall: Wiley-Blackwell.

ERICSSON, K.A. and SIMON, H.A., 1993. *Protocol analysis: verbal reports as data*. Cambridge MA: MIT Press.

F

FARRINGTON, B. and LYSONS, K., 2012. *Purchasing and Supply Chain Management*. Eighth edn. Essex, England: Pearson.

FELLOWS, R. and LIU, A., 2008. *Research methods for construction*. Malden, USA: Willey- Blackwell.

FISCHER, G., 2000. Symmetry of ignorance, social creativity, and meta-design. *Knowledge-Based Systems,* **1**3(7–8), pp. 527-537.

FLYVBJERG, B., BRUZELIUS, N. and ROTHENGATTER, W., 2003. *Megaprojects and Risk: An Anatomy of Ambition*. Cambridge University Press.

FOQUE, R. and LAMMINEUR, M., 1995. Designing for patients: a strategy for introducing human scale in hospital design. *Design Studies,* **1**6(1), pp. 29-49.

FRANCIS, J.J., JOHNSTON, M., ROBERTSON, C., GLIDEWELL, L., ENTWISTLE, V., ECCLES, M.P. and GRIMSHAW, J.M., 2010. What is an adequate sample size? Operationalising data saturation for theory-based interview studies. *Psychology & Health,* **2**5(10), pp. 1229-1245.

FRASCARI, M., 2011. *Eleven exercises in the art of architectural drawing [electronic resource] : slow food for the architect's imagination*. Oxon: Taylor & Francis.

FRENCH, M.J., 1971. *Engineering Design: the conceptual stage*. London, UK: Heinemman Educational.

FROESE, T.M., 2010. The impact of emerging information technology on project management for construction. *Automation in Construction,* **1**9(5), pp. 531-538.

FROESE, T.M., 2005. Impact of Emerging Information Technology on Information Management, *International Conference on Computing in Civil Engineering, ASCE, Cancun, Mexico, Paper 889*0, July 12-15 2005, pp. 10 pgs.

FRY, B., 2008. *Visualising Data*. Sevastopol, CA, USA: O'Reilly.

G

GABRIEL, G.C. and MAHER, M.L., 2002. Coding and modelling communication in architectural collaborative design. *Automation in Construction*, 11(2), pp. 199-211.

GANN, D.M., SALTER, A.J. and WHYTE, J.K., 2003. Design quality indicator as a tool for thinking. *Building Research & Information,* **3**1(5), pp. 318-333.

GARNER, S. and MANN, P., 2003. Interdisciplinarity: perceptions of the value of computer-supported collaborative work in design for the built environment. *Automation in Construction,* **1**2(5), pp. 495-499.

GERO, J.S. and MC NEILL, T., 1998. An approach to the analysis of design protocols. *Design Studies,* **1**9(1), pp. 21-61.

GLASER, B.G. and STRAUSS, A., 1967. *The discovery of grounded theory: Strategies for qualitative research*. Chicago: IL: Aldine.

GOEL, A.K., VATTAM, S., WILTGEN, B. and HELMS, M., 2012. Cognitive, collaborative, conceptual and creative — Four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design. *Computer-Aided Design,* **4**4(10), pp. 879-900.

GRAPHISOFT BIMx. Available: http://www.graphisoft.com/products/bim-explorer/ [10/03, 2012].

Graphisoft BIMx. Available: http://www.graphisoft.com/bimx/ [04/02, 2015].

GRILO, A. and JARDIM-GONCALVES, R., 2011. Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective. *Automation in Construction,* 20(2), pp. 107-114.

GROSS, M.D., 1996. The Electronic Cocktail Napkin—a computational environment for working with design diagrams. *Design Studies,* **1**7(1), pp. 53-69.

GROSS, M.D. and YI-LUEN, D., 1996. Ambiguous intentions: a paper-like interface for creative design, *Proceedings of the 9th annual ACM symposium on User interface software and technolog*y 1996, pp. 183-192.

GTEAM [Homepage of Gehry Technologies], [Online]. Available: http://www.gteam.com/ [10/03, 2012].

GU, N., KIM, M.J. and MAHER, M.L., 2011. Technological advancements in synchronous collaboration: The effect of 3D virtual worlds and tangible user interfaces on architectural design. *Automation in Construction,* **2**0(3), pp. 270-278.

GU, N. and LONDON, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction,* **1**9(8), pp. 988-999.

GUEST, G., BUNCE, A. and JOHNSON, L., 2006. How many interviews are enough? An experiment with data saturation and variability. *Field Methods,* (18), pp. 59-82.

H

HALES, C., 1993. *Managing Engineering Design*. Harlow, UK: Longman Scientific &Technical.

HARTY, J. and LAING, R., 2011. Trust and Risk in Collaborative Environments, *Information Visualisation (IV), 2011 15th International Conference on Information Visualisatio*n 2011, pp. 558-563.

HARTY, J., 2012. *The impact of digitalisation on the management role of architectural technology*. [online] PhD Thesis, RGU.

HECHT, D., REINER, M. and HALEVY, G., 2006. Multimodal virtual environments: response times, attention, and presence. *Presence: Teleoper. Virtual Environ.,* 15(5), pp. 515-523.

HENRICH, D., Coordination Resolution - 40% Faster than Traditional Clash Detection. Available: http://www.vicosoftware.com/0/blogs/virtual-construction-lessons-and-insights/tabid/84142/bid/12818/Coordination-Resolution-40-Faster-than-Traditional-Clash-Detection.aspx [02/28, 2013].

HOK CHIEF EXECUTIVE OFFICER PATRICK MACLEAMY, FAIA, , The Future of the Building Industry (3/5): The Effort Curve [Homepage of HOK Network], [Online]. Available: http://www.youtube.com/watch?v=9bUlBYc_Gl4&feature=relmfu [11/15, 2012].

HORVATH, I., 2012. Recent developments in computer supported cooperative work in design: From group collaboration through global connectivity to informing apobetics, *Computer Supported Cooperative Work in Design (CSCWD), 2012 IEEE 16th International Conference o*n 2012, pp. 2-13.

HORVÁTH, I. and VROOM, R.W., 2015. Ubiquitous computer aided design: A broken promise or a Sleeping Beauty? *Computer-Aided Design,* **5**9(0), pp. 161-175.

HSU, W. and LIU, B., 2000. Conceptual design: issues and challenges. *Computer-Aided Design,* 32(14), pp. 849-850.

HUNTER, K. and KELLY, J., 2008. Grounded Theory. In: A. KNIGHT and L. RODDOCK, eds, *Advanced Researh Methods in the Built Environment*. West Susex, UK: Wiley-Blackwell, pp. 86-98.

I

ISENBERG, P., ELMQVIST, N., SCHOLTZ, J., CERNEA, D., MA, K. and HAGEN, H., 2011. Collaborative Visualisation: Definition, Challenges, and Research Agenda. *Information Visualisation,* **1**0(4), pp. 310-326.

ISHII, H. and ULLMER, B., 1997. Tangible bits: towards seamless interfaces between people, bits and atoms, *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems, CHI* '97 1997, pp. 234-241.

ISHII, H., UNDERKOFFLER, J., CHAK, D., PIPER, B., BEN-JOSEPH, E., YEUNG, L. and KANJI, Z., 2002. Augmented urban planning workbench: overlaying drawings, physical models and digital simulation, *Proceedings of ISMAR, IEE*E 2002.

J

JONSON, B., 2005. Design ideation: the conceptual sketch in the digital age. *Design Studies,* **2**6(6), pp. 613-624.

JUNGREIS, I. and LAUER, M.R., 2011. *Graphical object generation and regeneration*. United States.

K

KALAY, Y.E., 2004. *Architecture's new media: principles, theories, and methods of computer-aided design*. MIT Press.

KAN, H.Y., DUFFY, V.G. and SU, C., 2001. An Internet virtual reality collaborative environment for effective product design. *Computers in Industry,* **4**5(2), pp. 197-213.

KASSEM, M., IQBAL, N., KELLY, G., LOCKLEY, S. and DAWOOD, N., 2014. Building information modelling: protocols for collaborative design processes. *Journal of Information Technology in Construction (ITcon)*, 19, pp. 126-149.

KIM, M.J. and MAHER, M.L., 2008. The impact of tangible user interfaces on spatial cognition during collaborative design. *Design Studies,* **2**9(3), pp. 222-253.

KLEIN, M., SAYAMA, H., FARATIN, P. and BAR-YAM, Y., 2003. The Dynamics of Collaborative Design: Insights from Complex Systems and Negotiation Research. *Concurrent Engineering,* 11(3), pp. 201-209.

KOUTSABASIS, P., VOSINAKIS, S., MALISOVA, K. and PAPAROUNAS, N., 2012. On the value of Virtual Worlds for collaborative design. *Design Studies,* **3**3(4), pp. 357-390.

KREPS, G.L., 1989. *Organisation Communication: Theory and Practice*. 2nd edition edn. New York: Longman.

KRICK, V., 1969. *An introduction to Engineering and Engineering Design*. 2nd edn. New York, London, Sydney, Toronto: Wiley&Sons Inc.

KRUEGER, R.A., 1997. *Developing Questions for Focus Groups*. London: Sage Publications.

KRUEGER, R.A. and CASEY, M.A., 2009. *Focus Groups, A Practical Guide for Applied Research*. 4th Edition edn. London: Sage Publications.

KRUM, R., 2014. *Cool infographics: effective communication with data visualisation and design*. Wiley-Blackwell.

KYMMELL, W., 2008. *Building Information Modelling: Planning and Managing Construction Projects with 4D CAD and Simulations*. United States of America: McGraw-Hill Construction Professional.

L

LAMPEL, J., 2001. The core competencies of effective project execution: the challenge of diversity. *International Journal of Project Management,* **1**9(8), pp. 471-483.

LARSON, E., 1997. Partnering on construction projects: a study of the relationship between partnering activities and project success. *Engineering Management, IEEE Transactions on,* **4**4(2), pp. 188-195.

LATHAM, M., 1994. *Constructing the team: Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry*. Dept. of the Environment, HMSO.

LAWSON, B., 2005. *How Designers Think: The Design Process Demystified*. 4th edn. Amsterdam: Architectural Press, Elsevier.

LAWSON, B., 2004. *What Designers Know*. Oxford: Architectural Press, Elsevier.

LECOURTOIS, C., 2012. From Architecturology to Architecturological research. *Lusofona Journal of Architecture and Education,* Available at: <http://revistas.ulusofona.pt/index.php/revlae/article/view/2677/2040>. Date accessed: Feb. 2014.

LECOURTOIS C., 2011. Architecturological and epistemological research on collaborative design », *International Journal of Design Sciences and Technology*, 18 (1) 1, Europia productions, p. 31-46, 2011.

LEE, J. and JEONG, Y., 2012. User-centric knowledge representations based on ontology for AEC design collaboration. *Computer-Aided Design,* **44**(8), pp. 735-748.

LEVITT, R.E., VDT Computational Emulation Models of Organisations: State of the Art and Practice [Homepage of Virtual Design Team], [Online]. Available: http://www.stanford.edu/group/VDT/VDT.pdf [11/13, 2012].

LOCKLEY, S., 2011-last update, BIM and education. Available: http://www.thenbs.com/topics/bim/articles/bimAndEducation.asp [02/02, 2014].

LOO, R., 2003. Assessing "team climate" in project teams. *International Journal of Project Management,* 21(7), pp. 511-517.

LOREN G., T., 1995. Overview of human-computer collaboration. *Knowledge-Based Systems,* 8(2–3), pp. 67-81.

LOVE, P.E.D. and EDWARDS, D.J., 2004. Forensic project management: The underlying causes of rework in construction projects. *Civil Engineering and Environmental Systems,* **2**1(3), pp. 207-228.

LU, S.C., CAI, J., BURKETT, W. and UDWADIA, F., 2000. A Methodology for Collaborative Design Process and Conflict Analysis. *CIRP Annals - Manufacturing Technology,* 49(1), pp. 69-73.

LYYTINEN, K., YOO, Y., VARSHNEY, U., ACKERMAN, M., DAVIS, G., AVITAL, M., ROBEY, D., SAWYER, S. and SØRENSEN, C., 2004. Surfing the next wave: Design and implementation challenges of ubiquitous computing. *Communications of AIS,* 13(1), pp. 697-716.

M

MCDONALD, S., 2005. Studying actions in context: a qualitative shadowing method for organizational research. *Qualitative Research*, 5(4), pp. 455-473.

MACK, N., WOODSONG, C., MACQUEEN, K., GUEST, G. and NAMEY, E., 2005. *Qualitative research methods: a data collector's field guide*. USA: Family Health International (FHI).

MACMILLAN, S., STEELE, J., AUSTIN, S.A., SPENCE, R. and KIRBY, P., 1999. Mapping the early stages of the design process - a comparison between engineering and construction, *International conference on engineering design, ICED 99,* 1999.

MACMILLAN, S., STEELE, J., KIRBY, P., SPENCE, R. and AUSTIN, S., 2002. Mapping the design process during the conceptual phase of building projects. *Engineering, Construction and Architectural Management,* 9(3), pp. 174-180.

MACMILLAN, S., STEELE, J., AUSTIN, S., KIRBY, P. and ROBIN SPENCE, 2001. Development and verification of a generic framework for conceptual design. *Design Studies,* **2**2(2), pp. 169-191.

MALINS, J. and MCDONAGH, D., 2008. A Grand Day out: Empathic Approaches to Design, *International Conference on Engineering and Product Design Educatio*n 2008, pp. 198.

MCCALL, R., BENNETT, P., D'ORONZIO, P., OSTWALD, J., SHIPMAN, F. and WALLACE, N., 1990. PHIDIAS: A PHI-based design environment integrating CAD graphics into dynamic hypertext, *European Conference on Hypertex*t 1990.

MCCALL, R., VLAHOS, E. and ZABEL, J., 2001. Conceptual Design as HyperSketching. Theory and Java Prototype. , pp. 285-297.

MCMANUS, T.C., TISHMAN, D.R. and TURNBAUGH, L.R., 1996. Remedies for Delays in Architectural Construction. *Cost engineering,* 38(9), pp. 33-40.

MICROSOFT, Photosynth. Available: https://photosynth.net/about.aspx [02/04, 2015].

MIHIC, M., SERTIC, J. and ZAVRSKI, I., 2014. Integrated Project Delivery as Integration between Solution Development and Solution Implementation. *Procedia - Social and Behavioral Sciences,* 119(0), pp. 557-565.

MILES, M.B., HUBERMAN, A.M. and SALDANA, J., 2013. *Qualitative Data Analysis: A Methods Sourcebook*. 3rd edition edn. London: SAGE Publications.

MILGRAM, P. and KISHINO, F., 1994. A taxonomy of mixed reality visual displays, *IECE Transactions on Information and System*s 1994, pp. 1321-1329.

MOBACH, M.P., 2008. Do virtual worlds create better real worlds? *Virtual Reality,* 12(3), pp. 163-179.

MORGAN, L.D., 1997. *The Focus Group Guidebook: Focus Group Guidebook v. 1*. London: Sage Publications.

N

NATIONAL INSTITUTE OF BUILDING SCIENCES BUILDING SMART ALLIANCE, , The National BIM Standard-United States (MBIMS-US tm) Version 2. Available: http://www.nationalbimstandard.org/ [03/01, 2013].

NEWBY, P., 2009. *Research Methods for Education*. London: Routledge.

NILSSON, B., PETERSON, B., HOLDEN, G. and ECKERT, C., 2011. Design Med Omtanke: Participation and sustainability in the design of public sector buildings. *Design Studies,* 32(3), pp. 235-254.

O

OH, J. and STUERZLINGER, W., June 2004. A system for desktop conceptual 3D design. *Virtual Reality,* 7(3-4), pp. 198-211.

OH, J., STUERZLINGER, W. and DANAHY, J., 2006. SESAME: towards better 3D conceptual design systems , *Proceedings of the 6th conference on Designing Interactive systems (DIS '06)* 2006, pp. 80-89.

OKADA, H., 1999. Advance of precision engineering in the 1900s: history of computer aided design system. *J Japan Soc Precis Eng,* 65(1), pp. 7-12.

OLSEN, L., SAMAVATI, F.F., SOUSA, M.C. and JORGE, J.A., 2009. Sketch-based modeling: A survey. *Computers & Graphics,* 33(1), pp. 85-103.

ORLIKOWSKI, W.J., 1992. Learning from Notes: organisational issues in groupware implementation, *1992 ACM conference on Computer-supported cooperative work (CSCW '92*) 1992, ACM, pp. 362-369.

OSBORN, A., F., 1979. Applied imagination: principles and procedures of creative thinking. 3rd Revised edition edn. New York: Charles Scribner's Sons.

P

PAHL, G. and BEITZ, W., 1995. *Engineering design: a systematic approach*. second edn. Berlin, Germany: Springer.

PALLASMAA, J., 2009. *The thinking Hand: Existential and Embodied Wisdom in Arhitecture*. West Sussex: John Wiley & Sons.

PARK, M. and PEÑA-MORA, F., 2003. Dynamic change management for construction: introducing the change cycle into model-based project management. *System Dynamics Review,* **1**9(3), pp. 213-242.

PEETERS, M.A.G., VAN TUIJL, H.F.J.M., REYMEN, I.M.M.J. and RUTTE, C.G., 2007. The development of a design behaviour questionnaire for multidisciplinary teams. *Design Studies,* **2**8(6), pp. 623-643.

PENNY, R.K., 1970. Principles of engineering design. *Postgraduate medical journal,* 46(536), pp. 344-349.

PENTTILA, H., 2009. Services in Digital Design: new visions for AEC-field collaboration. *International Journal of Architectural Computing,* 7(3), pp. 459-478.

PHILP, D., February 2012-last update, BIM and the UK Construction Industry. Available: http://www.thenbs.com/topics/bim/articles/bimAndTheUKConstructionStrategy.asp [04/30, 2012].

PICCOLOTTO, A., 1998. *SketchPad+. Architectural Modeling through Perspective Sketching on Pen-based Display. Master of Science Thesis, Program of Computer Graphics.* Cornell University.

PRASAD, S., 2004a. Clarifying intentions: the design quality indicator. *Building Research & Information,* 32(6), pp. 548-551.

PRASAD, S., 2004b. Inclusive Maps. In: S. MACMILLAN, ed, *Designing Better Buildings.* London, UK: Spon Press.

PURCELL, T., GERO, J. and MCNEILL, T., 1996. The data in design protocols: the issue of data coding, data analysis in the development of models of the design process. In: N. CROSS, H. CHRISTIAANS and K. DORST, eds, *Analysing Design Activity.* Chichester: Wiley, pp. 225-252.

R

RANDY, D., 2011. Working With Others In BIM. *BIM and Integrated Design: Strategies for Architectural Practice.* New Jersey: John Wiley & Sons, pp. 91-126.

REDMOND, A., HORE, A., ALSHAWI, M. and WEST, R., 2012. Exploring how information exchanges can be enhanced through Cloud BIM. *Automation in Construction,* 24(0), pp. 175-183.

RHINO 3D. Available: http://www.rhino3d.com/ios [02/04, 2015].

RITTEL, H., 1984. Second-generation design methods. In: N. CROSS, ed, *Developments in Design Methodology.* Wiley, pp. 317-327.

RITTEL, W.H. and WEBBER, M.M., 1973. Dilemmas in a General Theory of Planning. *Policy Sciences,* 4(2), pp. 155-169.

ROD, M., 2011. Subjective personal introspection in action-oriented research. *Qual Research in Orgs & Mgmt,* 6(1), pp. 6-25.

RUSSELL, P. and ELGER, D., 2008. The Meaning of BIM, *26th eCAADe Conference Proceeding*s, 17-20 September 2008 2008, eCAADe, pp. 531-536.

S

SALMAN, H., 2011. *The impact of CAAD on design methodology and visual thinking in architectural educatio*n, PhD Thesis, RGU. Available from: http://openair.rgu.ac.uk [03/12, 2014].

SALMAN, H., LAING, R. and CONNIFF, A., 2006. CAAD Visualisation Techniques Mediate the Conceptual Design Process as a Thinking Tool - Reflection on action study, *Communicating Space(s), 24th eCAADe Conference Proceeding*s 2006.

SALMAN, H.S., LAING, R. and CONNIFF, A., 2014. The impact of computer aided architectural design programs on conceptual design in an educational context. *Design Studies,* 35(4), pp. 412-439.

SALTER, J.D., CAMPBELL, C., JOURNEAY, M. and SHEPPARD, S.R.J., 2009. The digital workshop: Exploring the use of interactive and immersive visualisation tools in participatory planning. *Journal of environmental management,* 90(6), pp. 2090-2101.

Samsung SUR40 with Microsoft® PixelSense™ [Homepage of Samsung], [Online]. Available: http://www.samsung.com/us/business/displays/digital-signage/LH40SFWTGC/ZA [08/22, 2013].

SANOFF, H., 2000. *Community Participation Methods in Design and Planning*. New York: John Wiley & Sons.

SASS, L. and OXMAN, R., 2006. Materialising design: the implications of rapid prototyping in digital design. *Design Studies,* 27(3), pp. 325-355.

SCHAEKEN, W., VOOGHT, G.D., VANDIERENDONCK, A. and D'YDEWALLE, G., 1999. *Deductive Reasoning and Strategies*. New Jersey: Taylor & Francis.

SCHÖN, D., 1991. *The Reflective Practitioner: How Professionals Think in Action*. London: Ashgate Publishing Limited.

SCHWEIKARDT, E. and GROSS, M.D., 2000. Digital clay: deriving digital models from freehand sketches. *Automation in Construction,* 9(1), pp. 107-115.

SCOTT, K., BAKKER, C. and QUIST, J., 2012. Designing change by living change. *Design Studies,* 33(3), pp. 279-297.

SENSOPIA, I., MagicPlan. Available: http://www.sensopia.com/english/index.html [02/04, 2015].

SHARPLES, M., JEFFERY, N., DU BOULAY, J.B.H., TEATHER, D., TEATHER, B. and DU BOULAY, G.H., 2002. Socio-cognitive engineering: A methodology for the design of human-centred technology. *European Journal of Operational Research,* **13**6(2), pp. 310-323.

SHEN, W., HAO, Q. and LI, W., 2008. Computer supported collaborative design: Retrospective and perspective. *Computers in Industry,* **5**9(9), pp. 855-862.

SIMON, H.A., 1973. The structure of ill structured problems. *Artificial Intelligence,* 4(3–4), pp. 181-201.

SINCLAIR, D., 2013. *Assembling a Collaborative Project Team: Practical tools including Multidisciplinary Schedules of Services*. London: RIBA Publishing.

SINCLAIR, D., ed, 2012. *BIM Overlay to the RIBA Outline Plan of Work*. *http://www.ribabookshops.com/uploads/b1e09aa7-c021-e684-a548-b3091db16d03.pdf*: RIBA.

SINGH, V., GU, N. and WANG, X., 2011. A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction,* **2**0(2), pp. 134-144.

SIVANATHAN, A., LIM, T., RITCHIE, J., SUNG, R., KOSMADOUDI, Z. and LIU, Y., 2015. The application of ubiquitous multimodal synchronous data capture in CAD. *Computer-Aided Design,* 59(0), pp. 176-191.

SMYTH, H. and EDKINS, A., 2007. Relationship management in the management of PFI/PPP projects in the UK. *International Journal of Project Management,* 25(3), pp. 232-240.

SNOW, C.P., 1993. *The Two Cultures*. Cambridge: Cambridge University Press.

STEMPFLE, J. and BADKE-SCHAUB, P., 2002. Thinking in design teams - an analysis of team communication. *Design Studies,* 23(5), pp. 473-496.

STRAUSS, A. and CORBIN, J., M., 1998. *Basics of Qualitative Research: Tehniques and Procedures for Developing Grounded Theory*. 2nd edn. London: SAGE.

STUMPF, S.C. and MCDONNELL, J.T., 2002. Talking about team framing: using argumentation to analyse and support experiential learning in early design episodes. *Design Studies,* 23(1), pp. 5-23.

SUCCAR, B., 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction,* 18(3), pp. 357-375.

SUN, W., STARLY, B., NAM, J. and DARLING, A., 2005. Bio-CAD modelling and its applications in computer-aided tissue engineering. *Computer-Aided Design,* 37(11), pp. 1097-1114.

SUWA, M., PURCELL, T. and GERO, J., 1998. Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies,* 19(4), pp. 455-483.

SUWA, M. and TVERSKY, B., 1997. What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies,* 18(4), pp. 385-403.

T

TIERNEY, T., 2007. *Abstract space : beneath the media surface*. Oxon: Taylor & Francis.

TONG, C. and SRIRAM, D., 1992. Chapter 1, Introduction. In: CHRISTOPHER TONG, ed, *Artificial Intelligence in Engineering Design*. Boston: Academic Press, pp. 1-53.

TRIVEDI, P. and SAGAR, V., 2010. Emerging trends of ubiquitous computing. *Int J Adv Comput Sci Appl,* **1**(3), pp. 72-74.

TUCKMAN, B.W., 1965. Developmental sequences in small groups. *Psychological Bulletin,* (63), pp. 384-399.

TUFTE, E., 1983. *The Visual Display of Quantitative Information*. Cheshire, Connecticut: Graphics Press.

TULLIS, T. and ALBERT, B., 2013. Chapter 6 - Self-Reported Metrics. In: T. TULLIS and B. ALBERT, eds, *Measuring the User Experience (Second Edition).* Boston: Morgan Kaufmann, pp. 121-161.

V

VAALAND, T.I., 2004. Improving project collaboration: start with the conflicts. *International Journal of Project Management,* **22**(6), pp. 447-454.

VAALAND, T.I. and HÅKANSSON, H., 2003. Exploring interorganisational conflict in complex projects. *Industrial Marketing Management,* **32**(2), pp. 127-138.

VALKENBURG, R. and DORST, K., 1998. The reflective practice of design teams. *Design Studies,* 19(3), pp. 249-271.

VAN DER AALST, W.M.P., 2007. Exploring the CSCW spectrum using process mining. *Advanced Engineering Informatics,* 21(2), pp. 191-199.

VITRUVIUS, P. and MORGAN, M.H., 1960. *Vitruvius: the ten books on architecture*. New York: Dover Publications.

X

XIE, Y., and SALVENDY, S., 2003. Awareness support for asynchronous engineering collaboration. *Hum. Factors Man.,* 13, pp. 97-113.

W

WANG, L., SHEN, W., XIE, H., NEELAMKAVIL, J. and PARDASANI, A., 2002. Collaborative conceptual design—state of the art and future trends. *Computer-Aided Design,* 34(13), pp. 981-996.

WARE, C., 2012. *Information Visualisation, Perception for Design*. Elsevier.

WEISER, M., 1993. Some Computer Science Issues in Ubiquitous Computing. *Commun. ACM,* 36(7), pp. 75-84.

WHYTE, J., 2004. *Virtual Reality and the Built Environment*. Oxford: Architectural Press.

WITTEN, I.H., FRANK, E. and HALL, M., 2011. *Data Mining: Practical Machine Learning Tools and Techniques*. Burlington, MA, USA: Morgan Kaufmann Publishers Inc, Elsevier.

WOODS, K.D. and WCER, 2014-last update, About Transana. Available: http://www.transana.org/2014].

Y

YAMAMOTO, Y. and NAKAKOJI, K., 2005. Interaction design of tools for fostering creativity in the early stages of information design. *International Journal of Human-Computer Studies,* 63(4–5), pp. 513-535.

YANG, J. and WEI, P., 2010. Causes of Delay in the Planning and Design Phases for Construction Projects. *Journal of Architectural Engineering,* 16(2), pp. 80-83.

Z

ZELEZNIK, R.C., HERNDON, K.P. and HUGHES, J.F., 2006. SKETCH: an interface for sketching 3D scenes, *ACM SIGGRAPH 2006 Courses (SIGGRAPH '06*) 2006.

ZHEN, S., BLAGOJEVIC, R. and PLIMMER, B., 2013. Tangeo: geometric drawing with tangibles on an interactive table-top, *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)* 2013, ACM, pp. 1509-1514.

ZUCKERMAN, O. and GAL-OZ, A., 2013. To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces. *International Journal of Human-Computer Studies,* **7**1(7–8), pp. 803-820.

0-9

53, 53 Design Application. Available: https://www.fiftythree.com/paper [02/04, 2015].

Appendix A: Concept Stages Summary

<table>
<tr><th>Design Process Method</th><th colspan="9">Initial Design Stages</th><th colspan="2">Further Design Stages</th></tr>
<tr><td>RIBA Plan of Work 2013

(Assembling a Collaborative Team)</td><td colspan="5">1. Preparation: Project Objectives, Business Case, Sustainability Issues, Initial Project Brief, Site Information, Feasibility Studies, Client’s Risk Profile, agreement on project programme, Assemble Project Team, Scope of Service, Design Responsibilities, BIM&Soft Landings Strategies, Information Exchanges, decide the appointment documents.</td><td colspan="4">2. Concept Design: outline design proposals (structural, services, landscape) outline specs, preliminary cost planning, Project Strategies (environmental, energy, ecology), Agreement on Initial Project Brief and Final Project Brief, Procurement Strategy, Design Responsibility, Project Manual, Software Strategy, BIM Execution Plan.</td><td colspan="2">3. Developed Design

4. Technical Design

5. Specialist Design</td></tr>
<tr><td>Office of Government Commence- OGC Gateway Process 2007

(Project/business centre process)</td><td colspan="2">Gate 0: Strategic Assessment (Establish Business Need)</td><td colspan="2">Gate 1: Business Justification (Develop Business Case)</td><td colspan="2">Gate 2: Procurement Strategy (Develop procurement Strategy)</td><td colspan="2">Gate 3: Investment Decision (Competitive Procurement)</td><td>Decision Point 1: OUTLINE DESIGN</td><td>Decision Point 2: Detailed Design</td><td>Gate 4: Readiness for Service</td></tr>
<tr><td>BIM Overlay to RIBA Plan of Work 2012</td><td colspan="3">Preparations: Appraisal

Clients needs and objectives, business case, sustainability, F.M., agree level of BIM, define BIM inputs-outputs</td><td colspan="4">Preparation: Design Brief

Initial Statement of Requirements into Design Brief, project sustainability and BIM procedures, Data Drop 1</td><td colspan="2">Design: Concept

Agreement on project Quality Plan including BIM, preparation of concept design, Data Drop 2</td><td colspan="2">Design: Design Development

Pre-Construction: Production Information, Tender Documentation, Tender Action</td></tr>
<tr><td>Salford Process Protocol (SPP)

(Project/business centre process)</td><td>Demonstrate the need</td><td colspan="2">Conception of need</td><td colspan="2">Outline Feasibility</td><td colspan="2">Substantive feasibility and outline financial athroty</td><td>Outline Conceptual Design</td><td>Full Conceptual Design</td><td colspan="2">Co-ordinated Design, procurement and financial authority

Production Information</td></tr>
<tr><td>CIC Scope of Services 2007

(Construction)</td><td colspan="3">Preparation (Stage 1)</td><td colspan="4">Concept (Stage 2)</td><td colspan="2">Design Development (Stage 3)</td><td colspan="2">Production Information (Stage 4)</td></tr>
</table>

Design Process Method	Initial Design Stages						Further Design Stages		
BS 7000: Part 4: 1996 Design Management Systems-Managing Design in **Construction**	Design Brief: Interpretation of the project brief, assigning responsibilities, brief development, consolidating brief			Conceptual Design: outline of the design process			Further Design Stages: Scheme Design, Detail Design, Information for Construction, Briefing related to Construction		
VDI 2221 (Verein Deutscher Ingenieure) 1993 **(Engineering)**	Clarification and Task definition	Specification	Determine functions and their structures	Function Structure	Research on solution principles and combinations	Principal solution	Divide into modules, Develop modules layout, complete overall layout, prepare production		
Schön 1991 **(Design)**	Identification of the design Problem		Decision		Reflection		Result		
Cross 1989 **(Design)**	Clarifying objectives	Establishing functions	Setting Requirements	Determining Characteristics	Generative Alternatives	Evaluating Alternatives	Identifying Opportuniti es	Clarifying Objectives	
Pahl and Beitz 1988 **(Engineering)**	Design Problem	Clarification of the Task and Goal Setting	System Analysis and Synthesis	Decision	System Evaluation	Decision	Embodimen t Design	Detail Desig n	Soluti on
Archer 1984 **(Engineering)**	Training Programming/ Experience Brief	Data collection	Analysis	Synthesis			Development	Communica tion Solution	

<table>
<tr><th>Design Process Method</th><th colspan="11">Initial Design Stages</th><th colspan="4">Further Design Stages</th></tr>
<tr><td>March 1984

(Engineering)</td><td colspan="3">Induction: Design Characterstics</td><td colspan="5">Induction: Evaluate</td><td colspan="3">Induction: Suppositions</td><td colspan="2">Production: Data Models, Describe, Design</td><td colspan="2">Deduction: Design Theories, Predict, performance</td></tr>
<tr><td>French 1971

(Engineering)</td><td>Need</td><td>Problem Analysis</td><td colspan="2">Statement of the Problem</td><td colspan="3">Conceptual Design</td><td colspan="3">Selected Schemes</td><td>Embodiment of schemes</td><td>Detailing</td><td colspan="3">Working Drawings</td></tr>
<tr><td>PRINCE 2 Method (Projects in Controlled Environments)

(Project/business centre process)</td><td colspan="2">Initiate a project:

Project Brief and Plan</td><td colspan="4">Initiating a project</td><td colspan="5">Controlling a Stage - Stages Execution</td><td colspan="4">Closing a Project</td></tr>
<tr><td>RIBA Plan on Work 1969</td><td colspan="2">Inception</td><td colspan="3">Feasibility</td><td colspan="4">Outline Proposals</td><td colspan="2">Scheme Design</td><td colspan="3">Detail Design</td><td>Production</td></tr>
</table>

Predicted iteration points

Decision Points

Appendix B: Project Brief for the Development of the Computational Design Tool

Application of interactive surfaces for computer mediated collaborative environments to support conceptual design

Project led by PhD Student: Marianthi Leon

Context:

Effective design collaboration during the early design stages in Architecture, Engineering, and Construction (AEC) industry is a condition for effective overall design and construction. Furthermore, architectural design requires a strongly visual approach to communication and means through which multiple disciples can collaborate effectively by bridging different professional viewpoints and creating a shared understanding among all stakeholders. This can be facilitated, supported and promoted through effective visualisation technologies and digital means.

Collaborative design processes and ideas generation methods implemented within emerging augmented reality technologies can be the drivers and enablers for a more efficient collaboration during the early design stages.

The aim of the research is to create a software application for the Microsoft Surface Table, which is going to be utilised for experiments on computer mediated collaboration through visual and tactile user interfaces of multidisciplinary teams of the AEC industry. This particular software application will be tested in multiple experiments with different types of users and in various design scenarios and the common focus will be on conceptual design (which can actually affect the design of the software).

Further research could include integration of human-computer interaction and augmented technologies (i.e. a immersive CAVE virtual environment, tabletop augmented reality environments, etc).

Cave Environment

http://www.aecbytes.com/buildingthefuture/2009/InnovativeTechnologies.html

Augmented Reality

https://www.bartlett.ucl.ac.uk/space-syntax/research/projects/round-table

Aims and Objectives

- Development of the Software:
    - A full-screen paint like application, which will be active even when opening other applications that can handle layers of canvas. Ability to draw on a white sheet of paper with a selection of palette tools. The application should be seen as an active desktop where people could open other applications but the "Paint canvas" would still be visible and active for others to work on it simultaneously.
    - Links to web browser and picture library with drag and drop of pictures. Bringing pictures on the working surface.

- Multiuser. Allowing multiple people to work on the canvas as well as other application at the same time.
- The software will automatically take snapshots of the work progress in often intervals.
- Ability to start a new canvas.

- The software will be tested and optimised accordingly for multidisciplinary collaborative studies.
  - It will be tested both by last year students of the AEC industry and active professionals and industrial partners.

Conceptual Drawing of the Software

Prerequisites for the student

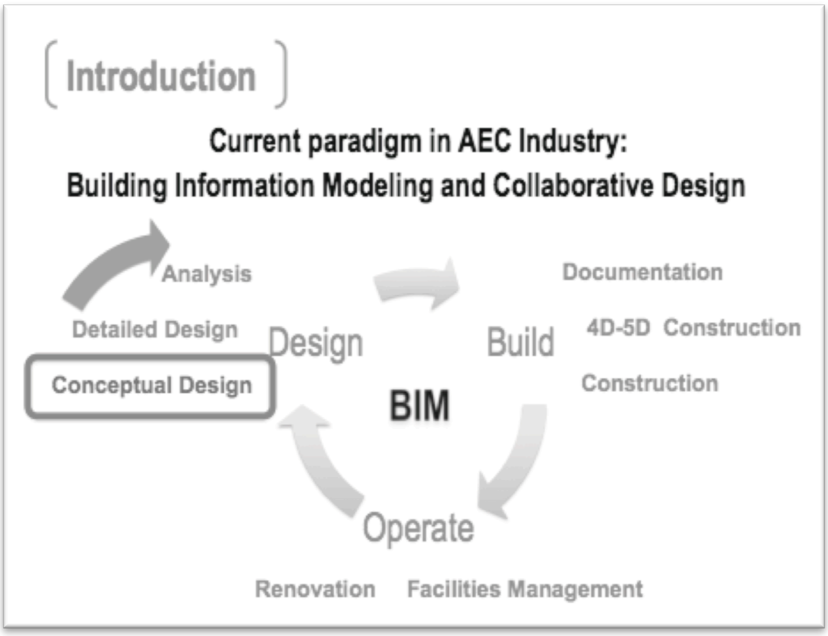
- Familiar with visual studio environment and C#.
- Concept of touchscreen environment as well as simultaneous multi-users inputs.
- The student should be keen to work on an actual Microsoft Surface (M.S. PixelSense) and be part of a multi-disciplinary project focus on the built environment and collaborative design.

Useful links:

- Training for the M.S. PixelSense

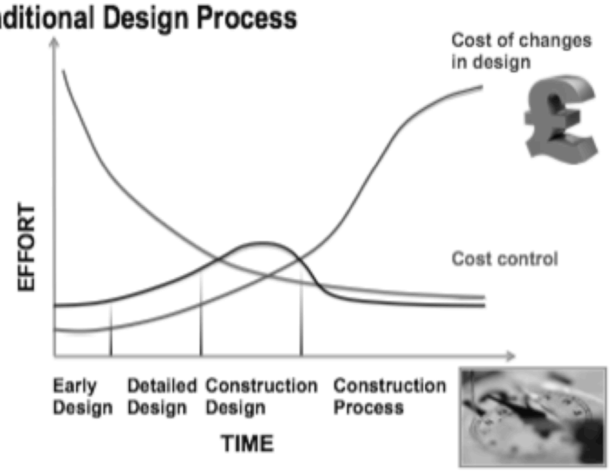
  http://www.microsoft.com/en-us/pixelsense/training20/index.html

Appendix C: Interviews Introductory Presentation



Collaborative Design in Conceptual Stage

Traditional Design Process



Collaborative Design in Conceptual Stage

Collaborative Design in the *Early Design Stages*

- **Concurrent engagement**
  of the different professionals during the decision making process.
- **Clash of ideas**
  between different professionals enhances creativity.
- **Overcoming the fragmentation**
  of the work stages between preparation and design.
- **Less turn backs**
  on later and more advanced design stages.

Collaborative Design in Conceptual Stage

Collaborative Design and ICT in the Early Design Stages

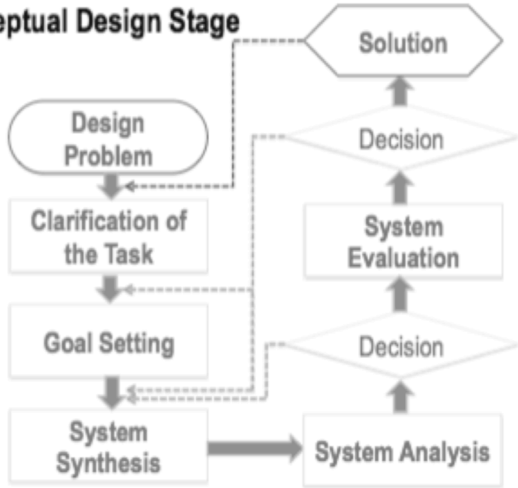
- **ICT- BIM aspects:**
  files exchange (IFCs), data organization, information flow, hierarchies and interactions.
- **Collaborative Design obstacles:**
  issues of workflow, education, team working, responsibility, computer mediated communication VS. face to face, synchronous-asynchronous collaboration, social aspects, etc.

Methodology

- **Establish and optimise a protocol for collaboration** during the early and conceptual design stages using digital collaborative tools.
- **Facilitate and test** both the current paradigm of conceptual design and the proposed protocol, and **undertake a critical comparison** between the two.

Methodology

Conceptual Design Stage

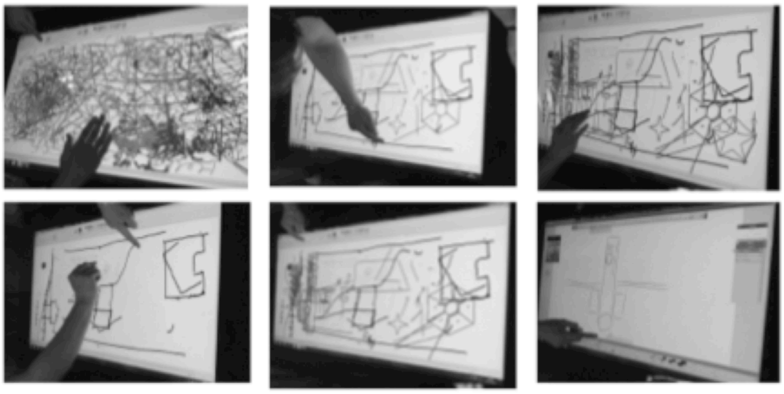


Case Studies

1st part of the Pilot Study: analogue means and the current paradigm

Case Studies

2nd part of the Pilot Study: digital means and the Microsoft Surface Table



Questions

- How do you achieve consensus during conceptual design?
- Which problems have you experienced during this process. Importantly, how do you then transfer these decisions into BIM/ computer models?
- What kind of information is necessary and which processes are assisting the design to move forward?
- How do you organize the team dynamics (in order to achieve design consensus)?
- (my aim is to make eventually the chaotic work especially during conceptual design stages, a bit more organized and smoother).

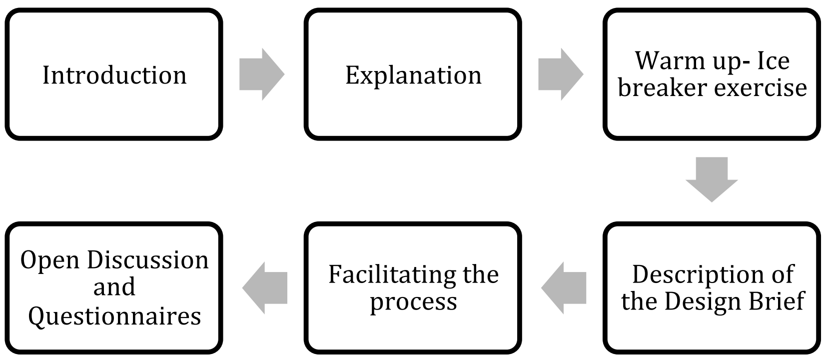
Appendix D: First Study Supporting Material

1. Design Brief

Research Focus Group on Conceptual Collaborative Design:

Design Brief

Focus Group Program:



Design Brief Description

Design Task:

The design task you are asked to complete is the conceptual design of a building that is going to be the working space for PhD and KTP students of the Scott Sutherland School.

The task you are asked to design is a working/office space, a relaxation area and other secondary/assisting spaces.

Issues to consider: what kind of space would you like to work and be in? What kind of facilities?

Building should include but not limited to:

Work space for current and future students (12-15 students on-off approximately).

Secondary spaces: kitchen, mail space, printing room, meeting room, wc, a shower room, a small exhibition space (either indoor or outdoor), etc.

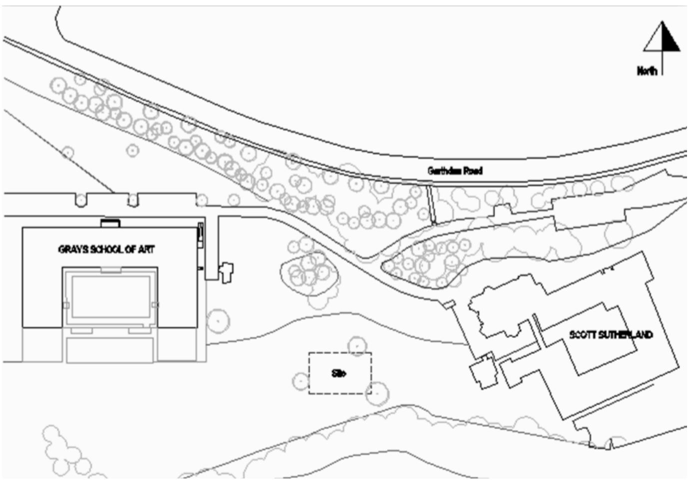
The available area is 200 sq.m. the maximum height 10m.

Aspects of the setting: river view, garden, display space, connections between different spaces.

Approximate sizes:

Working space	**Meeting Room**	**Kitchen**	**WC & shower**	**Printing room**	**Exhibition space**
75 sq.m.	15 sq.m.	10 sq.m.	3-5 sq.m.	3 sq.m.	…

Aerial view of the area



Drawing of the area

2. Questionnaires

Research Focus Group:

Monitoring Conceptual Collaborative Design

Questionnaire

Section 1: Conceptual design and computer mediation familiarity

1.1 Have you participated in conceptual design before Yes ☐ No ☐

1.2 Do you usually use computers during any stages of design?

Yes ☐ No ☐

1.3 If you are using a computer, during which design stage do you start using it?

Early Design Stages ☐

Detailed Design (DD) ☐

Construction Design (CD) ☐

Other:________________ ☐

1.4 Do you create 3D models using computer software? Yes ☐ ☐

No

1.5 How often do you use sketches during conceptual design stages?

Never	Sometimes	Always
☐	☐	☐
Why:		

1.6 Which is your preferable medium for drawing sketches?

Pen and paper ☐

Tablet sketching apps ☐

Design software (Autocad, 3dsMax, etc) ☐

Other:________________ ☐

Why (i.e. personal choice, professional experience, taught at school, etc):

1.7 Are you normally able to recognise your initial ideas in the final 'formal' drawings?

Yes ☐ No ☐

Why:

1.8 Do you keep notes during the conceptual design stages? ☐s ☐ No

Why:

1.9 If Yes, how do you store them and communicate them? (i.e. paper files in a cupboard, folders on computers, shared on a server for other to read/modify, etc. Are they used for communicating ideas and collaborating between different participants?)

Section 2: Feedback on the study

2.1 What did you think of the conceptual design process undertaken today?

2.2 How do you feel the multidisciplinary working affected the conceptual design process?

2.3 Which concepts/ideas did you explore?

2.4 How did you explore them?

2.5 What kinds of media did you use?

2.6 Which periods of the study were creative during the **first** part of the study? How did they promote the design process?

2.7 Which periods of the study were problematic during the **first** part of the study? How did you deal with them?

2.8 Which periods of the study were creative during the **second** part of the study? How did they promote the design process?

2.9 Which periods of the study were problematic during the **second** part of the study? How did you deal with them?

Section 3: Possible further development

3.1 What is your opinion about transferring hand drawn sketches to CAD/BIM software and platforms?

3.2 Would you consider it important or useful to include a tool for transferring pictures from the internet or other design databases to your design?

Not important	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	Very important
Why:						

3.3 Would (or do) you consider important to have a library with visual/ information database relevant to your discipline that you can create it and update it?

Not important	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	Very important
Why:						

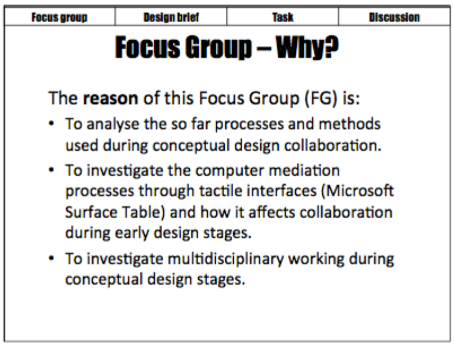
Section 4: Feedback on the survey methods and additional comments

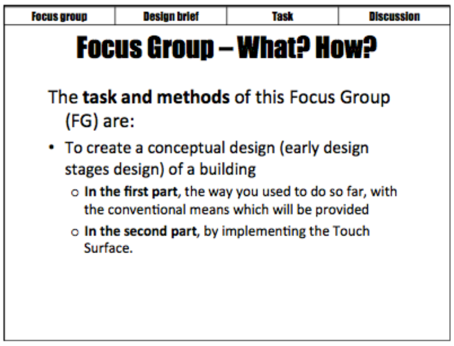
4.1 Do you have any suggestions on what to further include in this questionnaire?

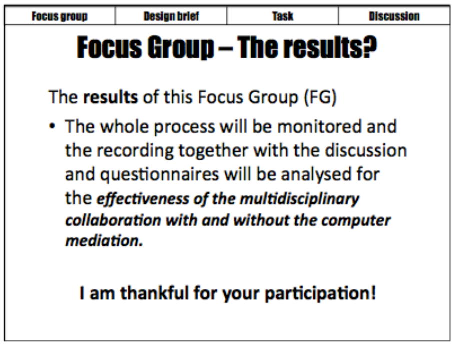
4.2 Additional comments (please use reverse if necessary)

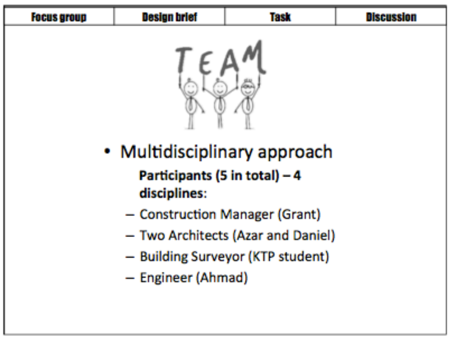
Thank you for your participation!

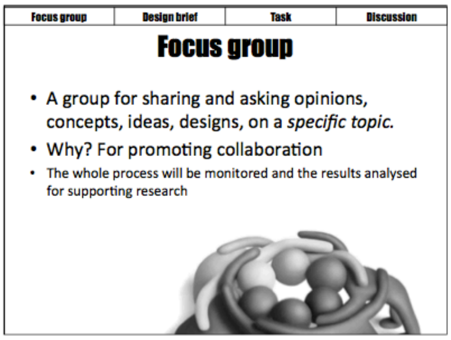
3. Facilitator's Presentation

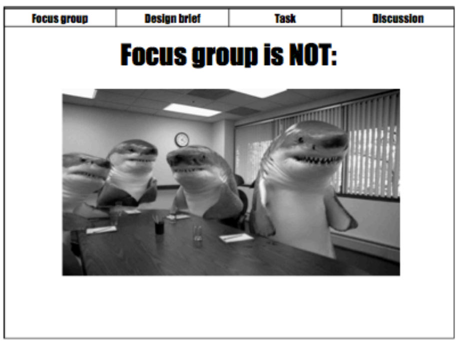


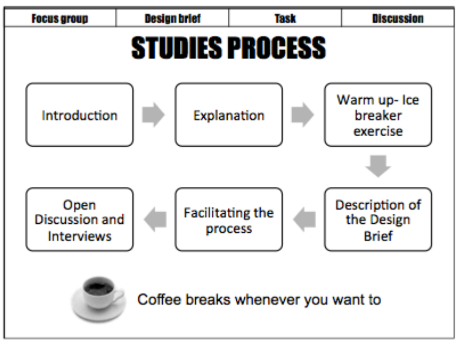












Focus group | Design brief | Task | Discussion

Ice breaker

- Introductions!

Which is your ***profession***?
What is your ***experience***?
Which are your ***strengths***?

Where will you go for holidays?

Focus group | Design brief | Task | Discussion

Design Brief

Design Task:

Conceptual design of a building which is going to be the working space for PhD and KTP students of the Scott Sutherland School.

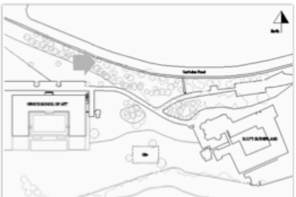
The task you are asked to design is a working/office space, a relaxation area and other secondary/assisting spaces.

Issues to consider: what kind of space would you like to work and be in? what kind of facilities?

Aspects of the setting: river view, garden, display space

Focus group | Design brief | Task | Discussion

Design Brief



The area is: between Grays School of Arts and SSS

Focus group | Design brief | Task | Discussion

Design Brief

Building should include but not limited to:

work space for current and future students (12-15 students on-off approximately),

kitchen, secondary spaces, mail space, printing room, meeting room, two wc, a shower room, etc.

The available area is 200 sq.m. the maximum height 10m.

Approximate space for the facilities:

working space	Meeting Room	Kitchen	WC & shower	Printing room	Exhibition space
75 sq.m.	15 sq.m.	10 sq.m.	3-5 sq.m.	3 sq.m.	...

Focus group | Design brief | Task | Discussion

Design Brief

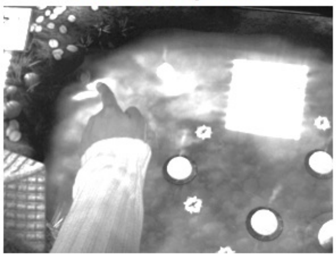
Focus group | Design brief | Task | Discussion

STUDIES PROCESS

Facilitating the Process

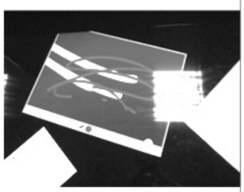
Focus group | Design brief | Task | Discussion

Warm up game



Focus group | Design brief | Task | Discussion

STUDIES PROCESS

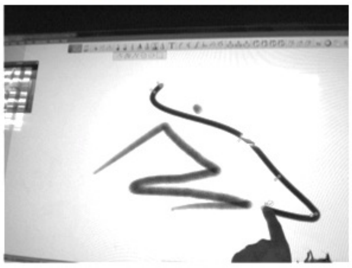


Focus group | Design brief | Task | Discussion

STUDIES PROCESS

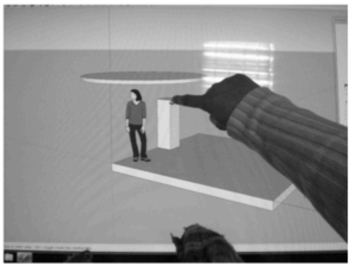
Focus group | Design brief | Task | Discussion

STUDIES PROCESS



Focus group | Design brief | Task | Discussion

STUDIES PROCESS



Focus group | Design brief | Task | Discussion

Discussion

Open Discussion and Interviews

- **End of the design task.**
- They are invited to discuss their process and the way they worked.
- Discussion about the overall experience.

Focus group | Design brief | Task | Discussion

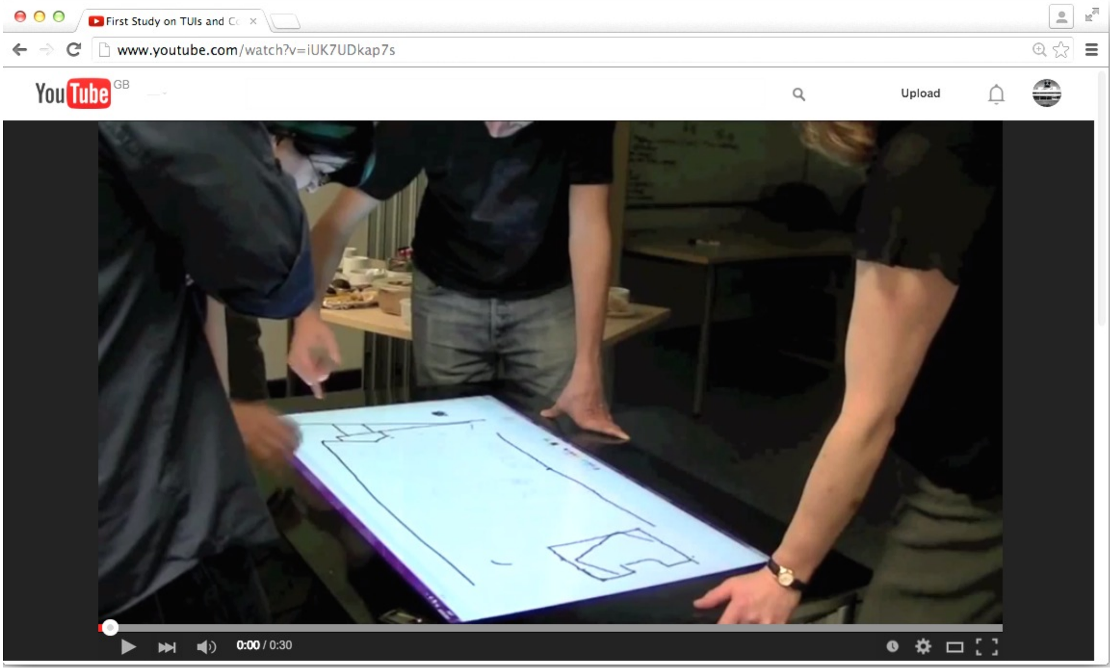
Discussion

(semi-structured open discussion)

- What do you think of the process?
- What are the concepts you explored?
- How did you explore them? Which was your process?
- What kind of media did you use?
- Which moments were creative? Which were problematic?
- How did you deal with these?
- What did you think of the provided means? Would you prefer something different?

4. Youtube Link:

http://www.youtube.com/watch?v=iUK7UDkap7s



Appendix E: Second Study Supporting Material

1. Design Brief

PROJECT EXECUTION PLAN

Design Research Hub

December 2013

Project Details

Project Details	**Project: Design Research Hub**	
Design Team	**Architects**	Azar & Daniel
	Quantity Surveyor	Rod
	M & E Engineer	Slimane
	Architect/ Structural Engineer	Ahmad
	Building Surveyor	Mike

Funding Details	**New Built** £ 2.5 million

Scope of the Project

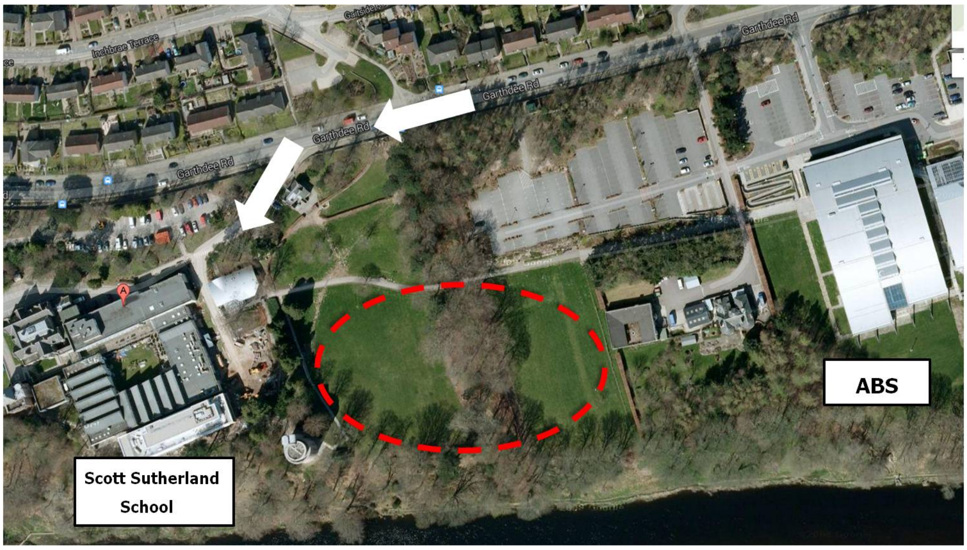
Background

Design a research base for Postgraduates in the fields of Design: from fabric and fashion design to architecture, industrial design, mechanical and electrical designs, urban design, etc.

Concept Design:

Project Deliverables	• **Outline Design Proposal** (architectural, structural, services, landscape, etc) • **Outline specs** • Preliminary **Cost Planning** • **Project Strategies** (environmental, energy, ecology)
Project Description	Qualities of Space: **Research groups** will be located within **open plan spaces** that they can set up and tailor to their needs. **Meeting spaces** are also required. **Flexible types of spaces** are necessary to adjust to teams' requirements for different time durations. **Workshops** for constructing physical models (facilitating 3d printing machines and laser cutting) together with **computer lab** and Virtual Reality facilities are also required. **Seminar**, **lecture** & **multipurpose rooms** are required to accommodate research needs. A **cafeteria**, **exhibition space** and a **design archive** are also part of the design brief. A high level of participation and research activity will take place in that building. **Links** with the rest of the **RGU Garthdee campus** buildings have to be established (pedestrian passages, light displays, etc).
Types of different spaces	• Offices for the different disciplines and research groups • Open plan space • Physical Models Workshop • Computers' Workshop • Seminar room(s) • Lecture room(s) • Multipurpose room • Cafeteria • Exhibition Space • Archive-Storage Additional facilities: • Kitchen/ Coffee Counter • WC& Shower room • Photocopier area • LAN Computer Room • First Aid Room • Reception

Site Information



B.S. and Regulations	**Specifications:** • Comply to the **BREEAM** specs for offices • Able to adapt to the 2020 **Zero-Energy Building** targets • Comply to **building regulations** • Allow for **further extension** in the future
Area	**Available area: 1.500-2.000 sp.m. approximately** **Building approximate gross sq.m.: 1.000** **Max high: 15 m. (from pedestrian street level)**
Number of people in the building	Currently 50 students (expected up to 80 students), 20-30 staff members approximately and 10 people support staff

Design Objectives

2. Questionnaires

Focus Group on Conceptual Collaborative Design

<u>Questionnaire</u> on BETA Test of the Protocol and the Software

Section 1: Conceptual design and computer mediation familiarity

Regarding each question, please cross (X) the relative box and briefly explain why, when asked.

1.1 Have you participated in conceptual design before? ☐ Yes ☐ No

1.2 How often you use computers during any stages of design?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.3 If you are using a computer, during which design stage do you start using it?

Early Design Stages ☐
Detailed Design (DD) ☐
Construction Design (CD) ☐
Other:________________________ ☐

1.4 How often do you use sketches during conceptual design stages?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.5 Are you normally able to recognise your initial ideas in the final 'formal' drawings?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.6 Which is your preferable medium for drawing sketches?

Pen and paper ☐
Tablet sketching apps ☐
Design software (Autocad, 3dsMax, etc) ☐

Other:______________________________ ☐

Why (i.e. personal choice, professional experience, taught at school/ work, etc)

1.7 Do you keep notes during the conceptual design stages? ☐S ☐ NO

Why:

1.7.a If YES, how do you store the information?

1.7.b If YES, how do you communicate the information?

Section 2: Feedback on the study

Regarding each question please score each with a cross (X) in the relative box following the scoring table given.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Part 1:

	Overall and group feedback	1	2	3	4	5
1	The overall collaborative team performance was successful and efficient					
2	The design that the group has produced for the task meets the aims of the design brief					
3	The group members' contribution to the task was sufficient and adequate					
4	The group has worked in an effective way					
5	The group was well organized					
6	The group has used the time efficiently					
7	The group benefited from multidisciplinary working					
8	The group decisions were effective and useful					
9	The final presentation of the concept helped to focus on an idea and clarify it					

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Part 2:

	Effectiveness of intended use of the Protocol	1	2	3	4	5
10	The overall collaborative Protocol process was efficient and helped to guide through the process					
11	The Protocol and the terminology were clearly understandable to me					
12	The design brief gave adequate level of information for the required task					
13	The design Protocol steps guided the design process					
14	The examples presented were useful to give ideas about the project					
13	The project specifications (sustainability issues and regulations) allowed for adequate level of detail during the conceptual design					
14	The business case (budget, available area, etc) allowed an adequate level of detail during the conceptual design					
15	The design objectives (functionality, built quality, impact) assisted for evaluating and finalising about the design					
16	The brainstorming tools were useful during the design					
17	The evaluation graph helped me evaluate the design					
18	The design Protocol was useful during the process					
19	The design Protocol assisted the collaboration					
20	The design Protocol further developed my understanding on collaborative and conceptual design					
21	The design Protocol is clear, realistic and usable in its present form					
22	The design Protocol is a realistic description of the steps undertaken during conceptual design					

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

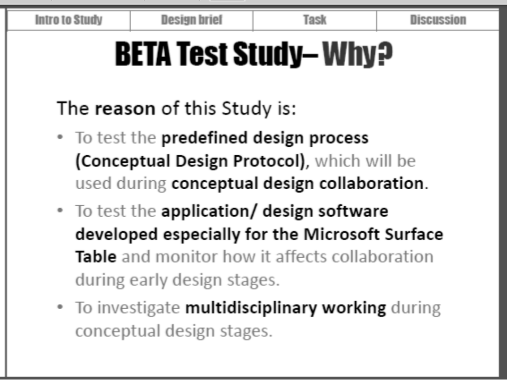
Part 3:

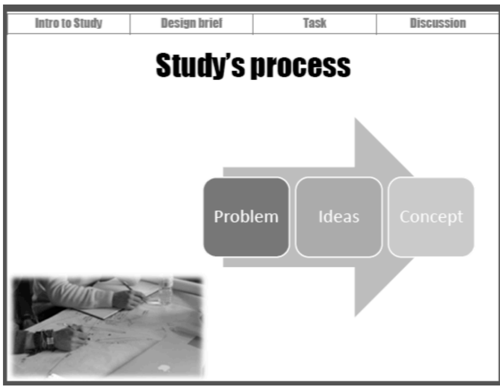
	User Satisfaction and Application Efficiency	1	2	3	4	5
23	My overall impression of the software is that it is uncomplicated and user friendly					
24	It's easy to draw on the Surface					
25	The icons/buttons are intuitive and easy to use					
26	The quality of the lines is good					
27	Taking a snapshot is easy and intuitive					
28	Text entry is easy and clear					
29	The importing images feature is useful					
30	It is easy to erase lines and clear the background					
31	I would be able to use the produced concepts and design for the detailed design					

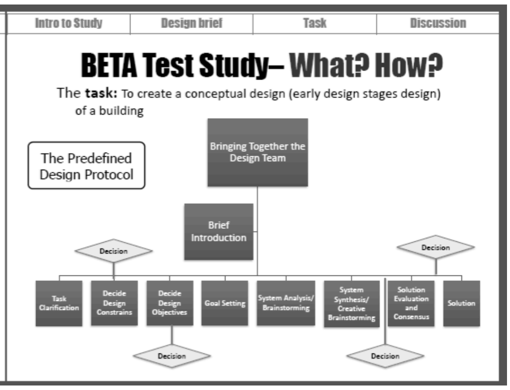
Additional Comments:

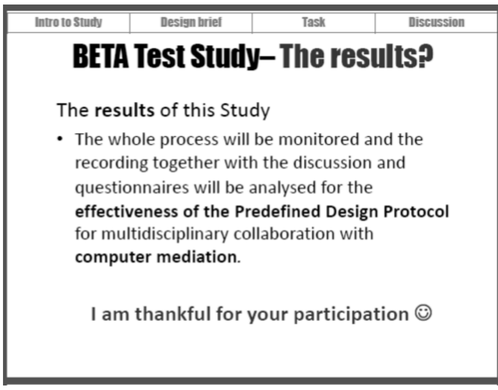
Thank you for your participation. Your feedback is of great value to the development of the design Protocol.

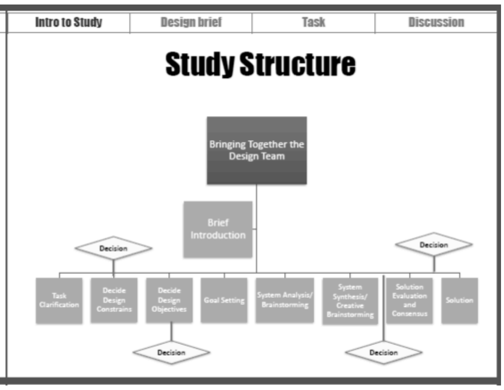
3. Facilitator's Presentation











Intro to Study | Design brief | Task | Discussion

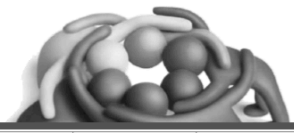
- Multidisciplinary approach

  Participants (6 in total) – 5 disciplines:
  - Architects (Azar and Daniel)
  - Architect- Structural Engineer (Ahmad)
  - Building Surveyor (Mike)
  - Mechanical Engineer (Slimane)
  - Quantity surveyor(Rod)

Intro to Study | Design brief | Task | Discussion

Study Group

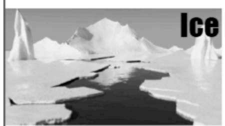
- A group for sharing and asking opinions, concepts, ideas, designs, on a *specific topic.*
- *Reason:* For promoting collaboration



Intro to Study | Design brief | Task | Discussion

Study group

Intro to Study | Design brief | Task | Discussion



Ice Breaker

Introduction:

Which is your *profession*?

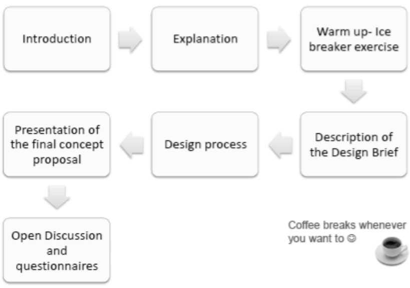
What is your *experience*?

Tell us your story on collaboration!

Which are your *strengths within a team*?

Intro to Study | Design brief | Task | Discussion

Study's process

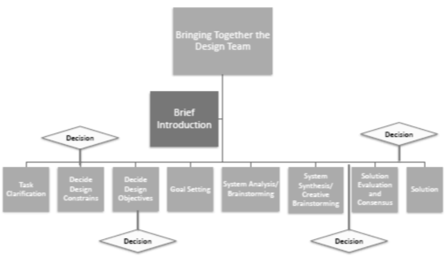


Intro to Study | Design brief | Task | Discussion

Microsoft Surface Table: Collaborative App

Intro to Study | Design brief | Task | Discussion

Design Brief



Intro to Study | Design brief | Task | Discussion

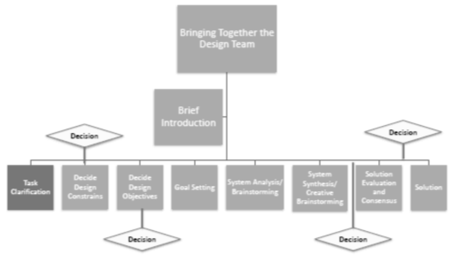
Design Brief

Conceptual Design Task:

Design Research Hub

A research base for Postgraduates in the fields of Design: from fabric and fashion design to architecture, industrial design, mechanical and electrical design, urban design, etc.

Task Clarification



Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Research groups** will be located within **open plan spaces** that they can set up and tailor to their needs. **Meeting spaces** are also required. **Flexible types of spaces** are necessary to adjust to teams' requirements for different time durations.

Workshops for constructing physical models (facilitating 3d printing machines and laser cutting) together with **computer lab** and Virtual Reality facilities is also required.

Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Seminar, lecture & multipurpose rooms** are required to accommodate research needs.

A **cafeteria, exhibition space** and a **design archive** are also part of the design brief. A high level of participation and research activity will take place in that building.

Links with the rest of the **campus** buildings have to be established (pedestrian passages, light displays, etc).

Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Research needs** are going to be evolving and the space has to reflect the changes (**evolve, adapt** and **grow**).

Issues to consider: The Hub aims at **promoting ideas** and professions **cross-pollination**; different types of researchers are going to interact as part of the building. Interaction with **industry** has also to be promoted and research outcomes are to be evaluated for industrial applications.

Task Clarification

Conceptual Design Task:

Design Research Hub

Space:

- Offices for the different disciplines and research groups
- Open plan space
- Physical Models Workshop
- Computers' Workshop
- Seminar room(s)
- Lecture room(s)
- Multipurpose room
- Cafeteria
- Exhibition Space
- Archive-Storage

Additional facilities:

- Kitchen/ Coffee Counter
- WC& Shower room
- Photocopier area
- LAN Computer Room
- First Aid Room
- Reception

Task Clarification

Conceptual Design Task:

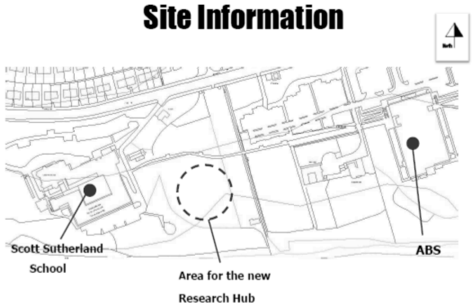
Design Research Hub

Space:

Reflection: what kind of space would you like to work and be in? what kind of facilities?

Aspects of the setting: River view, garden, display space

Site Information



Site Information

Sustainability Issues and Regulations

Conceptual Design Task:

Design Research Hub

Specifications:

- Comply to the **BREEAM** specs for offices
- Able to adapt to the 2020 **Zero-Energy Building** targets
- Comply to **building regulations**
- Allow for **further extension** in the future

Business Case

Conceptual Design Task:

Design Research Hub

Specifications

Budget: £2.5 million

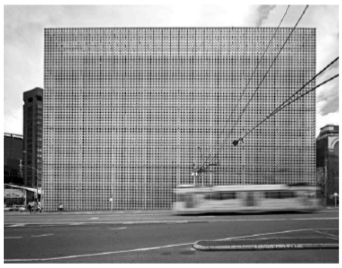
Available Area: 1.500 sq.m.

Max high: 15 m.

Building approximate gross sq.m. : 1.000

Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub



Intro to Study | Design brief | Task | Discussion

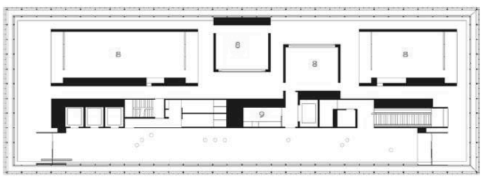
EXAMPLES: RMIT Design Hub

Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

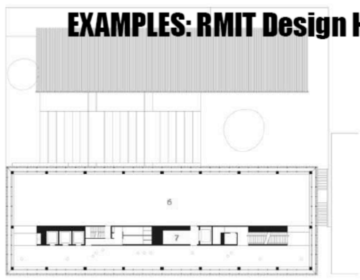


FIFTH FLOOR

1 LECTURE HALL
2 LOBBY
3 ARCHIVES
4 MEETING ROOM
5 MECHANICAL
6 STUDIOS ("WAREHOUSE")
7 STORAGE
8 SEMINAR
9 KITCHEN
10 ARCHIVES-DISPLAY RAMP
11 DISPLAY
12 EXHIBITION
13 CAFÉ

Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub



1 LECTURE HALL
2 LOBBY
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6 STUDIOS ("WAREHOUSE")
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8 SEMINAR
9 KITCHEN
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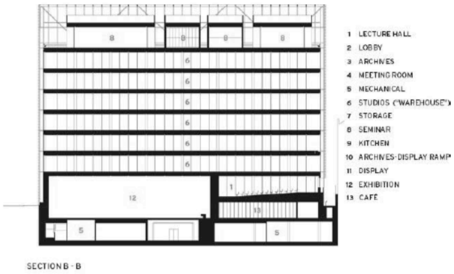
12 EXHIBITION
13 CAFÉ

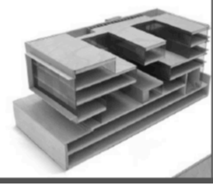
SECOND FLOOR

EXAMPLES: RMIT Design Hub

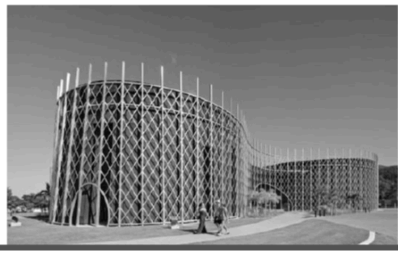


EXAMPLES: Andalusian Institute of Biotechnology

EXAMPLES: Andalusian Institute of Biotechnology

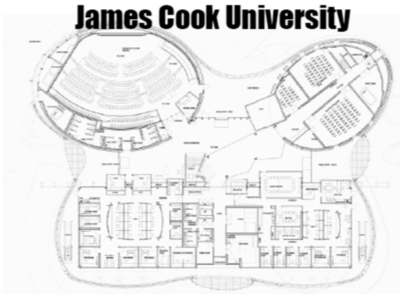


EXAMPLES: The Cairns Institute – James Cook University



EXAMPLES: The Cairns Institute – James Cook University

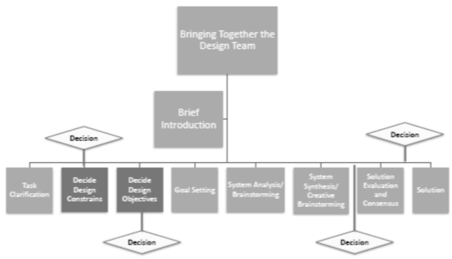
EXAMPLES: The Cairns Institute – James Cook University



Columbia University School of Nursing

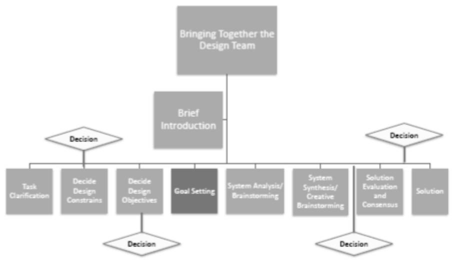
Columbia University School of Nursing

Decide Design Constrains



Decide Design Objectives

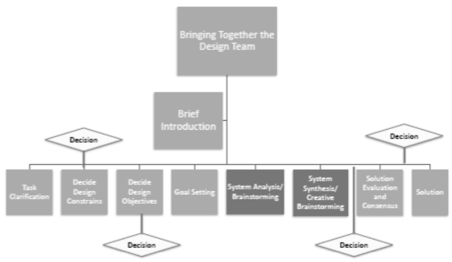
Goal Setting



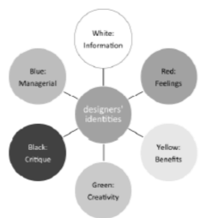
Goal Setting

- **Concept Design**
  - Outline Design Proposal (architectural, structural, services, landscape, etc)
  - Outline specs
  - Preliminary Cost Planning
  - Project Strategies (environmental, energy, ecology)

System Analysis and Synthesis: Creative Brainstorming



Methods for Creative Brainstorming



- **Methods:**
  - **Lateral thinking (6 thinking hats or 10 faces of innovation)**
  - **Mind maps**
  - **Benefits maps**

Creative Brainstorming

Decide a Solution

Decide the Solution

- **Which solution best answers the objectives?**

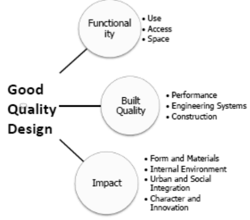
Creative Brainstorming

Decide a Solution

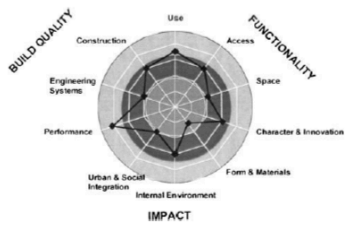
Evaluate the Solution & reach design team consensus

Evaluate the Solution

- **Have we completed the Design Concept?**
  - Outline Design Proposal (architectural, structural, services, landscape, etc)
  - Outline specs
  - Preliminary Cost Planning
  - Project Strategies (environmental, energy, ecology)
- **Have we achieved the objectives?**



Evaluate the Solution



Presentation of the final concept proposal

Discussion

- **What do you think of the multidisciplinary collaborative design?**
- What are the concepts you explored?
- How did you explore them? Which was your process?
- How do you evaluate the solution?
- How did the Protocol assist the design process?
- Which moments were creative?
- What did you think of the provided means? (i.e. The Surface App, the laptop, analogue means, etc.)
- Any further suggestions for the Microsoft Table?

Discussion

- What do you think of the multidisciplinary collaborative design?
- **What are the concepts you explored?**
- **How did you explore them? Which was your process?**
- **How do you evaluate the solution?**
- How did the Protocol assist the design process?
- Which moments were creative?
- What did you think of the provided means? Would you prefer something different?
- Any further suggestions for the Microsoft Table?

Discussion

- What do you think of the multidisciplinary collaborative design?
- What are the concepts you explored?
- How did you explore them? Which was your process?
- How do you evaluate the solution?
- **How did the Protocol assist the design process?**
- **Which moments were creative?**
- What did you think of the provided means? (i.e. The Surface App, the laptop, analogue means, etc.)
- Any further suggestions for the Microsoft Table?

Discussion

- What do you think of the multidisciplinary collaborative design?
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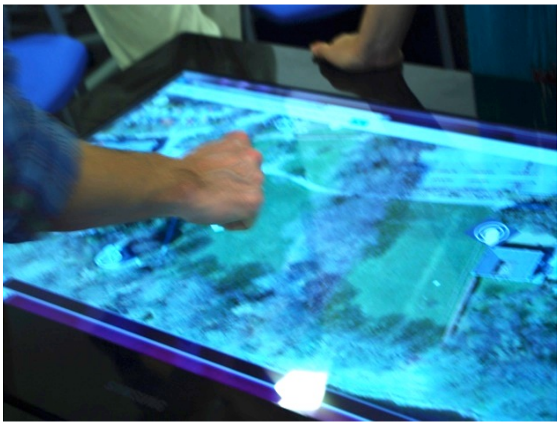
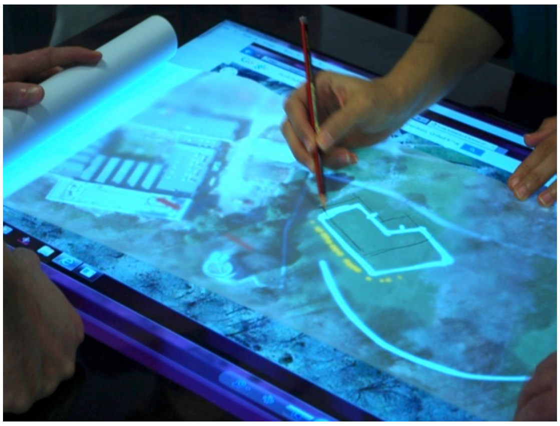
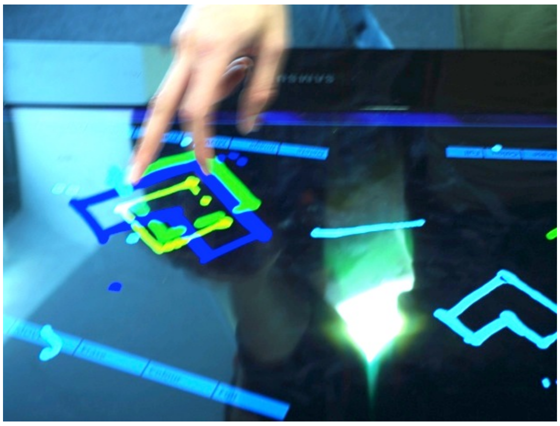
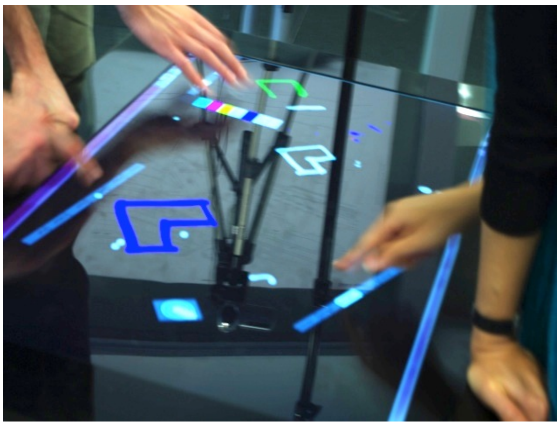
- How did you explore them? Which was your process?
- How do you evaluate the solution?
- How did the Protocol assist the design process?
- Which moments were creative?
- **What did you think of the provided means? (i.e. The Surface App, the laptop, analogue means, etc.)**
- **Any further suggestions for the Microsoft Table?**

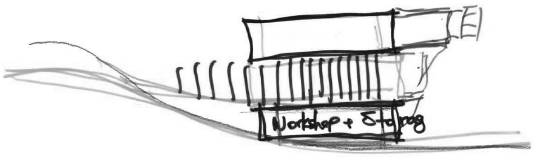
4. Participants sketches and notes

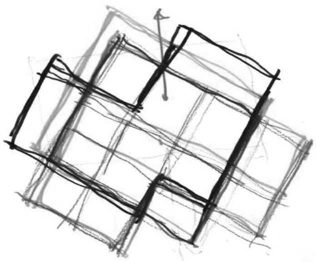


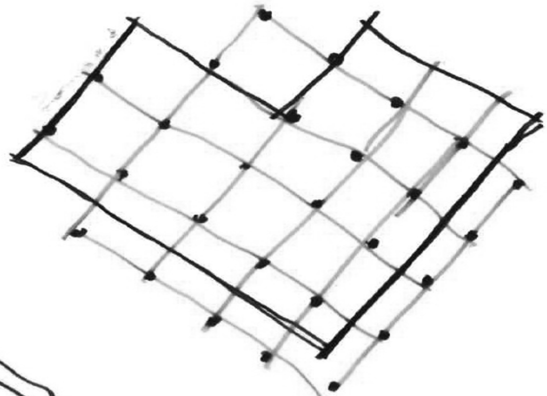


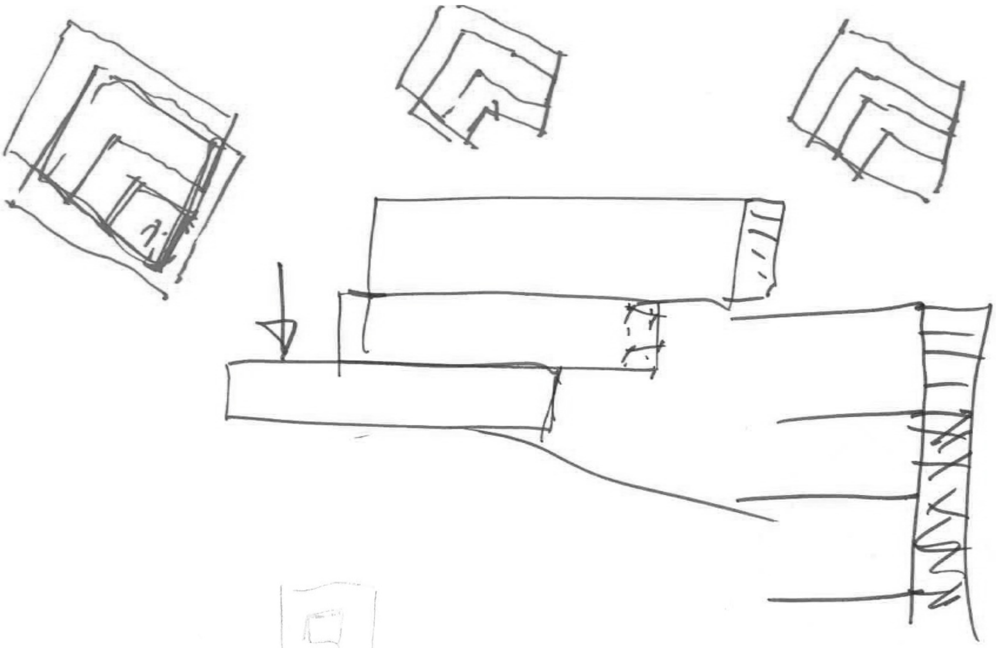


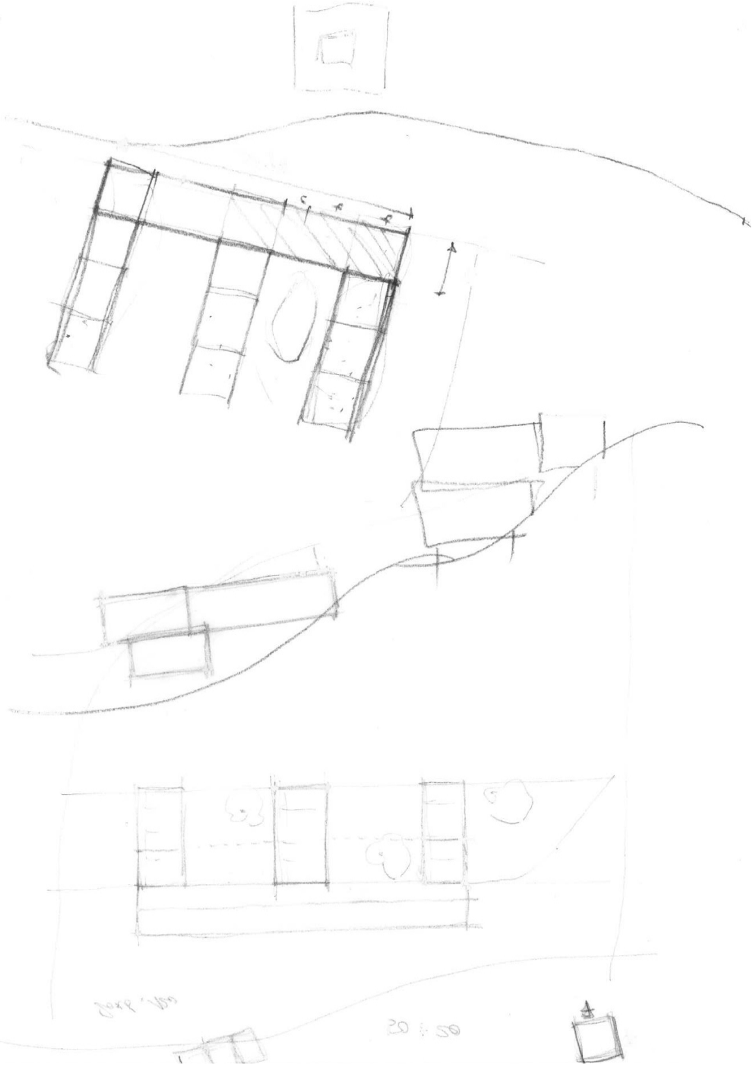


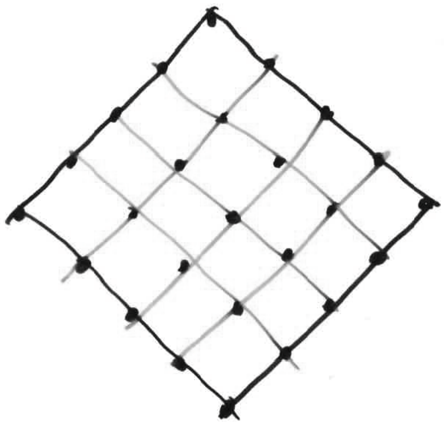

Workshop + Storag

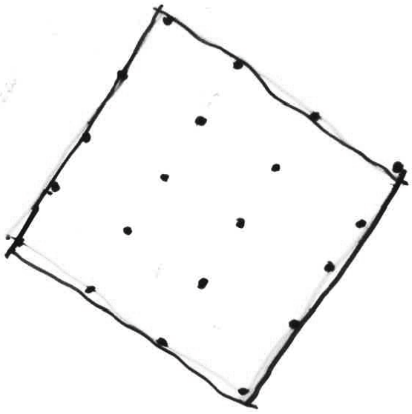


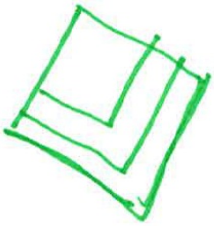


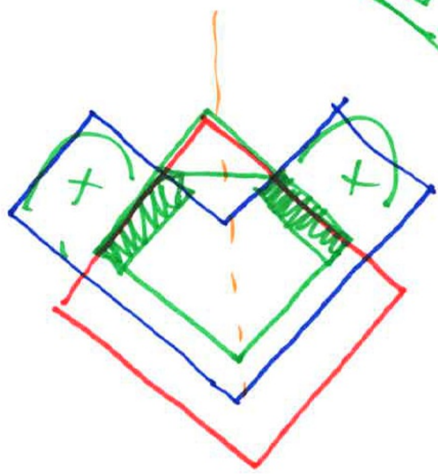


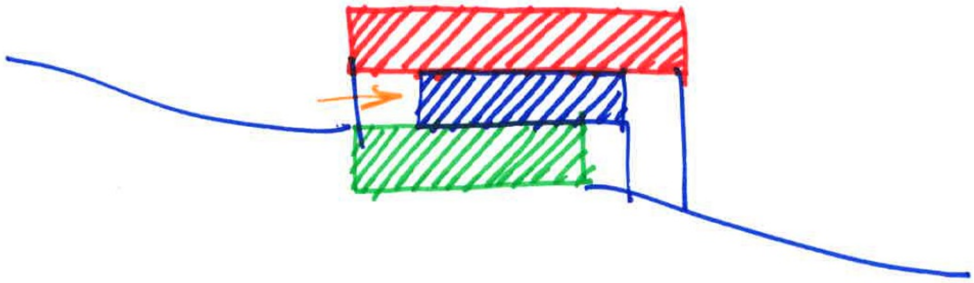






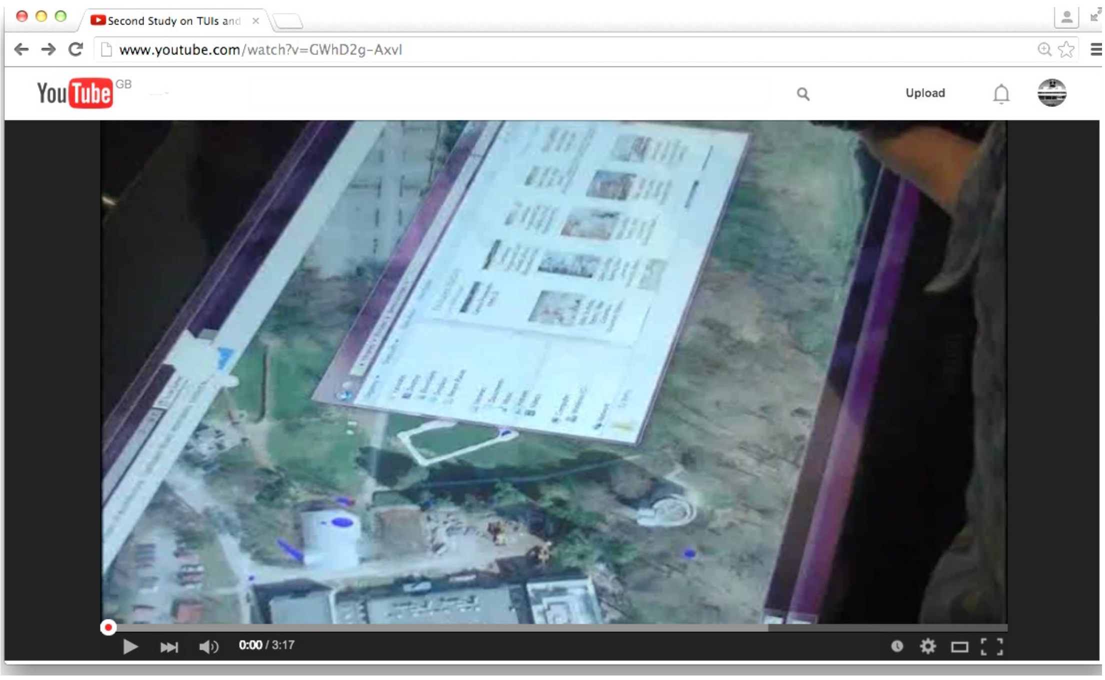






5. Youtube Link:

https://www.youtube.com/watch?v=GWhD2g-AxvI



Appendix F: Third Study Supporting Material

1. Design Brief

PROJECT EXECUTION PLAN

Design Research Hub

April 2014

Project Details

Project Details	**Project: Design Research Hub**	
Design Team	**Architects**	Gary & Kadum
	Architectural Technologist	Magdalena
	Quantity Surveyors	Daniel & Jack

Funding Details	**New Build**	£ up to 2.5 million

Scope of the Project

Background

Design a workshop and research base for Postgraduates in the fields of Architecture and Built Environment Design: from architecture and architectural technology to quantity and building surveying and construction management.

Project Deliverables

Concept Design:

- **Outline Design Proposal** (architectural, services, landscape)
- **Outline specs**
- Preliminary **Cost Planning**
- **Project Strategies** (environmental, energy, ecology)

Project Description

Qualities of Space: **A small Research group, both for undergrads and postgrads,** for Scott Sutherland School of Architecture and the Built Environment will be located within **open plan space** that they can set up and tailor to their needs. **Meeting spaces** are also required. **Flexible types of spaces** are necessary to adjust to teams' requirements for different time durations.
One Workshop for constructing physical models (facilitating 3d printing machines and laser cutting) together with **computer lab** is also required.
A multipurpose room is required to accommodate research needs.
A **cafeteria**, **exhibition space** and a **design archive** are also part of the design brief. A high level of participation and research activity will take place in that building.
Links with the rest of the **RGU Garthdee campus** buildings have to be established (pedestrian passages, light displays, etc.).

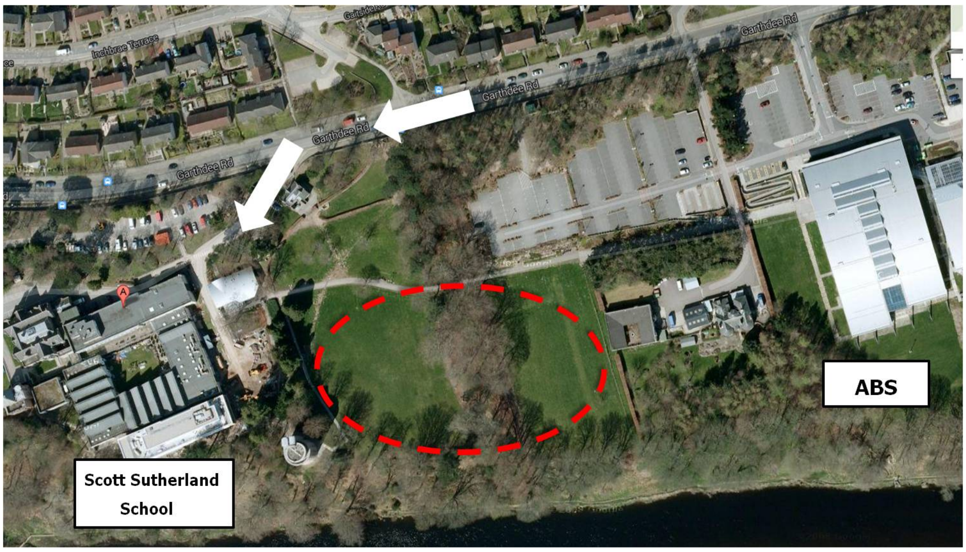
Types of different spaces and sq.m.

- Office space for four different disciplines (Architectural Technologists, Construction Managers, Architects, Surveyors) **[300 sq.m. in total]**
- One Physical Models Workshop **[100 sq.m.]**
- One Computers' Workshop **[60 sq.m.]**
- A Seminar/ Lecture room **[up to150 sq.m.]**
- Multipurpose room and/ or Exhibition space **[up to 150 sq.m.]**
- Cafeteria **[up to 50 sq.m.]**
- Archive-Storage **[100 sq.m.]**
- **20% more for circulation purposes**

Additional facilities – 30 sq.m.

- Kitchen/ Coffee Counter (maybe together with the cafeteria?)
- WC& Shower room
- Photocopier area
- LAN Computer Room
- First Aid Room
- Reception

Site Information



B.S. and Regulations	**Specifications:** • Able to adapt to the 2020 **Zero-Energy Building** targets • Comply to **building regulations**
Area	**Available area: 1.500-2.000 sp.m. approximately** **Building approximate gross sq.m.: 1.200** **Max high: 20 m. (from pedestrian street level)**
Number of people in the building	Up to 60 students and 10 staff members and 5 people support staff
Design Objectives	

2. Questionnaires

Focus Group on Conceptual Collaborative Design

Questionnaire on the Study for testing the Protocol and the Application

Section 1: Conceptual design and computer mediation familiarity

Regarding each question, please cross (X) the relative box and briefly explain why, when asked.

1.1 Have you participated in conceptual design before? YES☐ NO ☐

1.2 How often you use computers during any stages of design?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.3 If you are using a computer, during which design stage do you start using it?

Early Design Stages ☐
Detailed Design (DD) ☐
Construction Design (CD) ☐
Other:________________________ ☐

1.4 How often do you use sketches during conceptual design stages?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.5 Are you normally able to recognise your initial ideas in the final 'formal' drawings?

Never	Infrequently	Sometimes	Frequently	Always
☐	☐	☐	☐	☐
Why:				

1.6 Which is your preferable medium for drawing sketches?

Pen and paper ☐

Tablet sketching apps ☐
Design software (Autocad, 3dsMax, etc) ☐
Other:______________________________ ☐

Why (i.e. personal choice, professional experience, taught at school/ work, etc)

1.7 Do you keep notes during the conceptual design stages?
YES ☐ NO ☐

Why:

1.7.a If YES, how do you <u>store</u> the information?

1.7.b If YES, how do you <u>communicate</u> the information?

Section 2: Feedback on the study

Regarding each question please score each with a cross (X) in the relative box following the scoring table given.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

<u>Part 1:</u>

	Overall and group feedback	**1**	**2**	**3**	**4**	**5**
1	The overall collaborative team performance was successful and efficient					
2	The design that the group has produced for the task meets the aims of the design brief					
3	The group members' contribution to the task was sufficient and adequate					
4	The group has worked in an effective way					
5	The group was well organized					
6	The group has used the time efficiently					
7	The group benefited from multidisciplinary working					
8	The group decisions were effective and useful					
9	The final presentation of the concept helped to focus on an idea and clarify it					

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Part 2:

	Effectiveness of intended use of the Protocol	1	2	3	4	5
10	The overall collaborative Protocol process was efficient and helped to guide through the process					
11	The Protocol and the terminology were clearly understandable to me					
12	The design brief gave adequate level of information for the required task					
13	The design Protocol steps guided the design process					
14	The examples presented were useful to give ideas about the project					
13	The project specifications (sustainability issues and regulations) allowed for adequate level of detail during the conceptual design					
14	The business case (budget, available area, etc) allowed an adequate level of detail during the conceptual design					
15	The design objectives (functionality, built quality, impact) assisted for evaluating and finalising about the design					
16	The brainstorming tools were useful during the design					
17	The evaluation graph helped me evaluate the design					
18	The design Protocol was useful during the process					
19	The design Protocol assisted the collaboration					
20	The design Protocol further developed my understanding on collaborative and conceptual design					
21	The design Protocol is clear, realistic and usable in its present form					
22	The design Protocol is a realistic description of the steps undertaken during conceptual design					

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

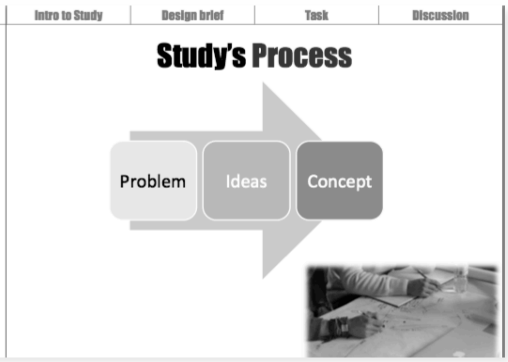
Part 3:

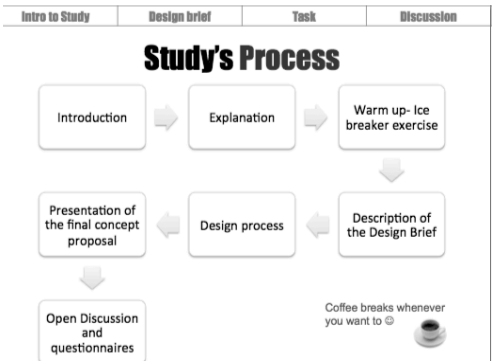
	User Satisfaction and Application Efficiency	1	2	3	4	5
23	My overall impression of the software is that it is uncomplicated and user friendly					
24	It's easy to draw on the Surface					
25	The icons/buttons are intuitive and easy to use					
26	The quality of the lines is good					
27	Taking a snapshot is easy and intuitive					
28	Text entry is easy and clear					
29	The importing images feature is useful					
30	It is easy to erase lines and clear the background					
31	I would be able to use the produced concepts and design for the detailed design					
32	Drawing with brushes is straightforward and easy					
33	The pictures' library is useful					
34	It is easy to draw on the pictures					
35	Layering the pictures is straightforward and intuitive					
36	The tag input is useful and intuitive					

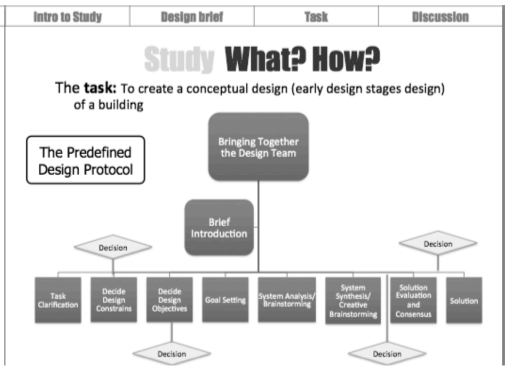
Additional Comments:

Thank you for your participation. Your feedback is of great value to the development of the design Protocol.

3. Facilitator’s Presentation







Intro to Study | Design brief | Task | Discussion

Study The results?

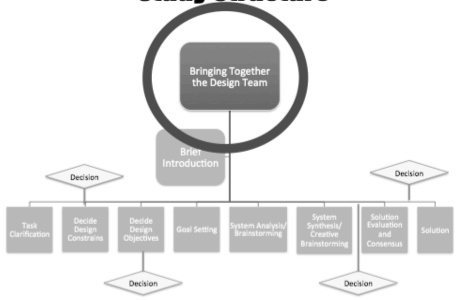
The **results** of this Study

The whole process will be monitored and the recording together with the discussion and questionnaires will be analysed for the **effectiveness of the Predefined Design Protocol** for multidisciplinary collaboration with **computer mediation**.

I am thankful for your participation ☺

Intro to Study | Design brief | Task | Discussion

Study Structure



Intro to Study | Design brief | Task | Discussion

Study The TEAM

- Multidisciplinary approach
  Participants → 3 disciplines:
  - Two Architects (Gary and Kadum)
  - One Architectural Technologist (Magdalena)
  - Two Building Surveyors (Daniel and Jack)

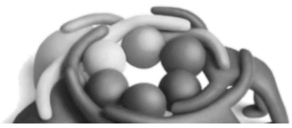
Intro to Study | Design brief | Task | Discussion

Study group

Intro to Study | Design brief | Task | Discussion

Study group

- A group for sharing and asking opinions, concepts, ideas, designs, on a *specific topic.*
- *Reason:* For promoting collaboration



Intro to Study | Design brief | Task | Discussion

Ice Breaker

Introduction:

Which is your *profession*?

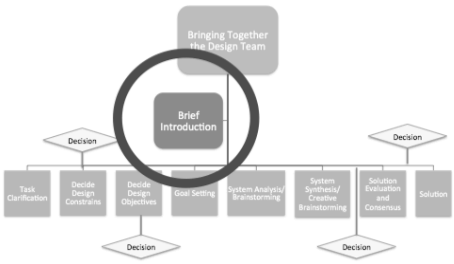
What is your *experience*?

Tell us your story on collaboration!

Which are your *strengths within a team*?

Intro to Study | Design brief | Task | Discussion

Design Brief



Intro to Study | Design brief | Task | Discussion

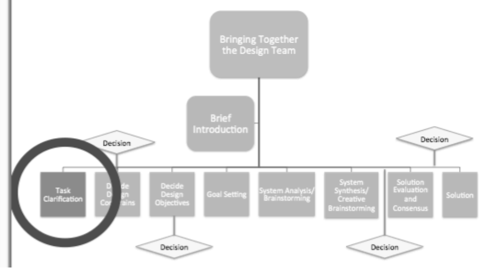
Design Brief

Conceptual Design Task:

Design Research Hub

A research base for Postgraduates in the fields of of Architecture and Built Environment Design: from architecture and architectural technology to quantity and building surveying and construction management.

Task Clarification



Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Research groups** will be located within **open plan spaces** that they can set up and tailor to their needs. **Meeting spaces** are also required. **Flexible types of spaces** are necessary to adjust to teams' requirements for different time durations.

Workshops for constructing physical models (facilitating 3d printing machines and laser cutting) together with **computer lab** and Virtual Reality facilities is also required.

Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Seminar, lecture & multipurpose rooms** are required to accommodate research needs.

A **cafeteria, exhibition space** and a **design archive** are also part of the design brief. A high level of participation and research activity will take place in that building.

Links with the rest of the **campus** buildings have to be established (pedestrian passages, light displays, etc).

Task Clarification

Conceptual Design Task:

Design Research Hub

Qualities of Space: **Research needs** are going to be evolving and the space has to reflect the changes (**evolve, adapt** and **grow**).

Issues to consider: The Hub aims at **promoting ideas** and professions **cross-pollination**; different types of researchers are going to interact as part of the building. Interaction with **industry** has also to be promoted and research outcomes are to be evaluated for industrial applications.

Task Clarification

Conceptual Design Task:

Design Research Hub

Space:

- Offices for the different disciplines and research groups
- Open plan space
- Physical Models Workshop
- Computers' Workshop
- Seminar room(s)
- Lecture room(s)
- Multipurpose room
- Cafeteria
- Exhibition Space
- Archive-Storage

Additional facilities:

- Kitchen/ Coffee Counter
- WC& Shower room
- Photocopier area
- LAN Computer Room
- First Aid Room
- Reception

Task Clarification

Conceptual Design Task:

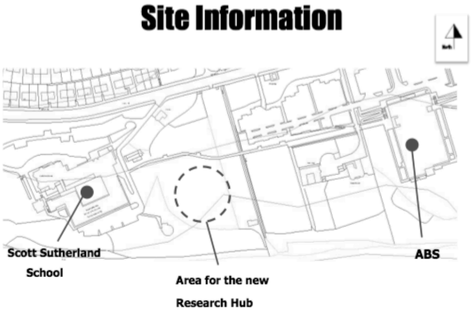
Design Research Hub

Space:

Reflection: what kind of space would you like to work and be in? what kind of facilities?

Aspects of the setting: River view, garden, display space

Site Information



Site Information

Sustainability Issues and Regulations

Conceptual Design Task:

Design Research Hub

Specifications:

- Comply to the **BREEAM** specs for offices
- Able to adapt to the 2020 **Zero-Energy Building** targets
- Comply to **building regulations**
- Allow for **further extension** in the future

Intro to Study | Design brief | Task | Discussion

Business Case

Conceptual Design Task:

Design Research Hub

Specifications

Budget: £2.5 million

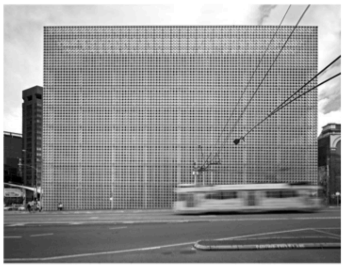
Available Area: 1.500 sq.m.

Max high: 15 m.

Building approximate gross sq.m. : 1.000

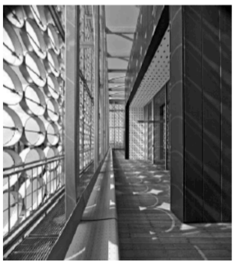
Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub



Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

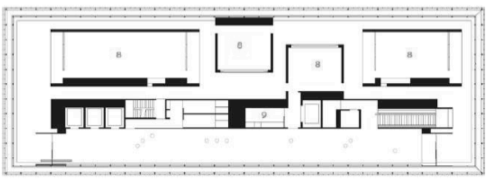


Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

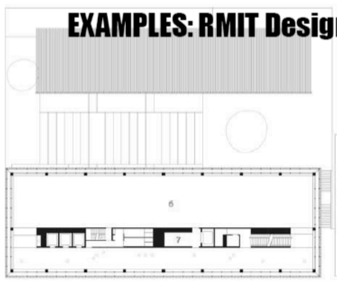
Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

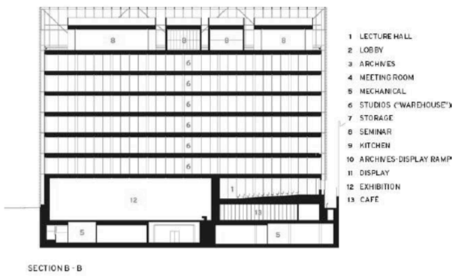


Intro to Study | Design brief | Task | Discussion

EXAMPLES: RMIT Design Hub

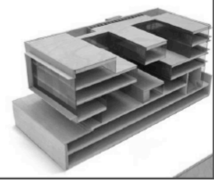


EXAMPLES: RMIT Design Hub

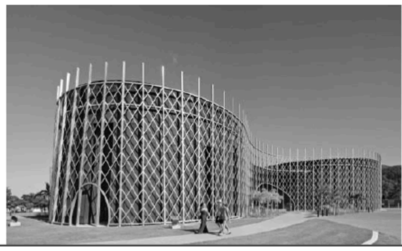


EXAMPLES: Andalusian Institute of Biotechnology

EXAMPLES: Andalusian Institute of Biotechnology



EXAMPLES: The Cairns Institute – James Cook University



EXAMPLES: The Cairns Institute – James Cook University

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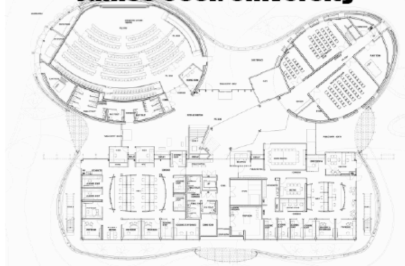
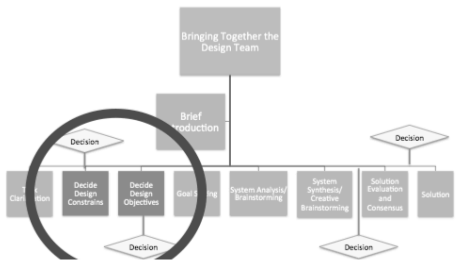


Columbia University School of Nursing

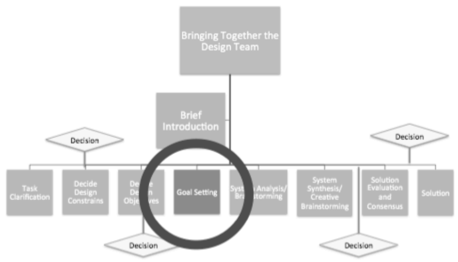
Columbia University School of Nursing

Decide Design Constrains



Decide Design Objectives

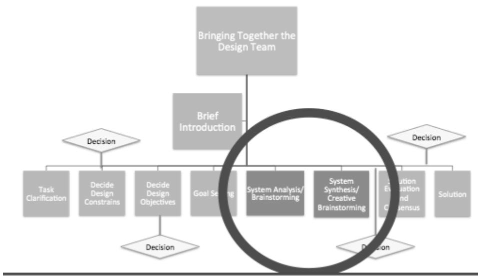
Goal Setting



Goal Setting

- **Concept Design**
  - Outline Design Proposal (architectural, structural, services, landscape, etc)
  - Outline specs
  - Preliminary Cost Planning
  - Project Strategies (environmental, energy, ecology)

System Analysis and Synthesis: Creative Brainstorming



Methods for Creative Brainstorming

- **Methods:**
  - **Lateral thinking (6 thinking hats or 10 faces of innovation)**
  - **Mind maps**
  - **Benefits maps**

Creative Brainstorming

Decide a Solution

Decide the Solution

- **Which solution best answers the objectives?**

Decide the Solution

- Which solution best answers the objectives?

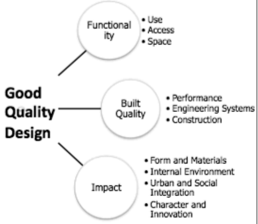
Creative Brainstorming

Decide a Solution

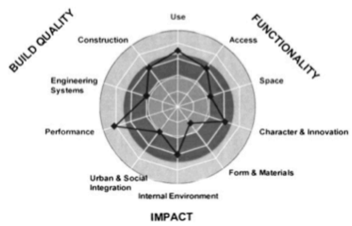
Evaluate the Solution & reach design team consensus

Evaluate the Solution

- Have we completed the Design Concept?
  - Outline Design Proposal (architectural, structural, services, landscape, etc)
  - Outline specs
  - Preliminary Cost Planning
  - Project Strategies (environmental, energy, ecology)
- Have we achieved the objectives?



Evaluate the Solution

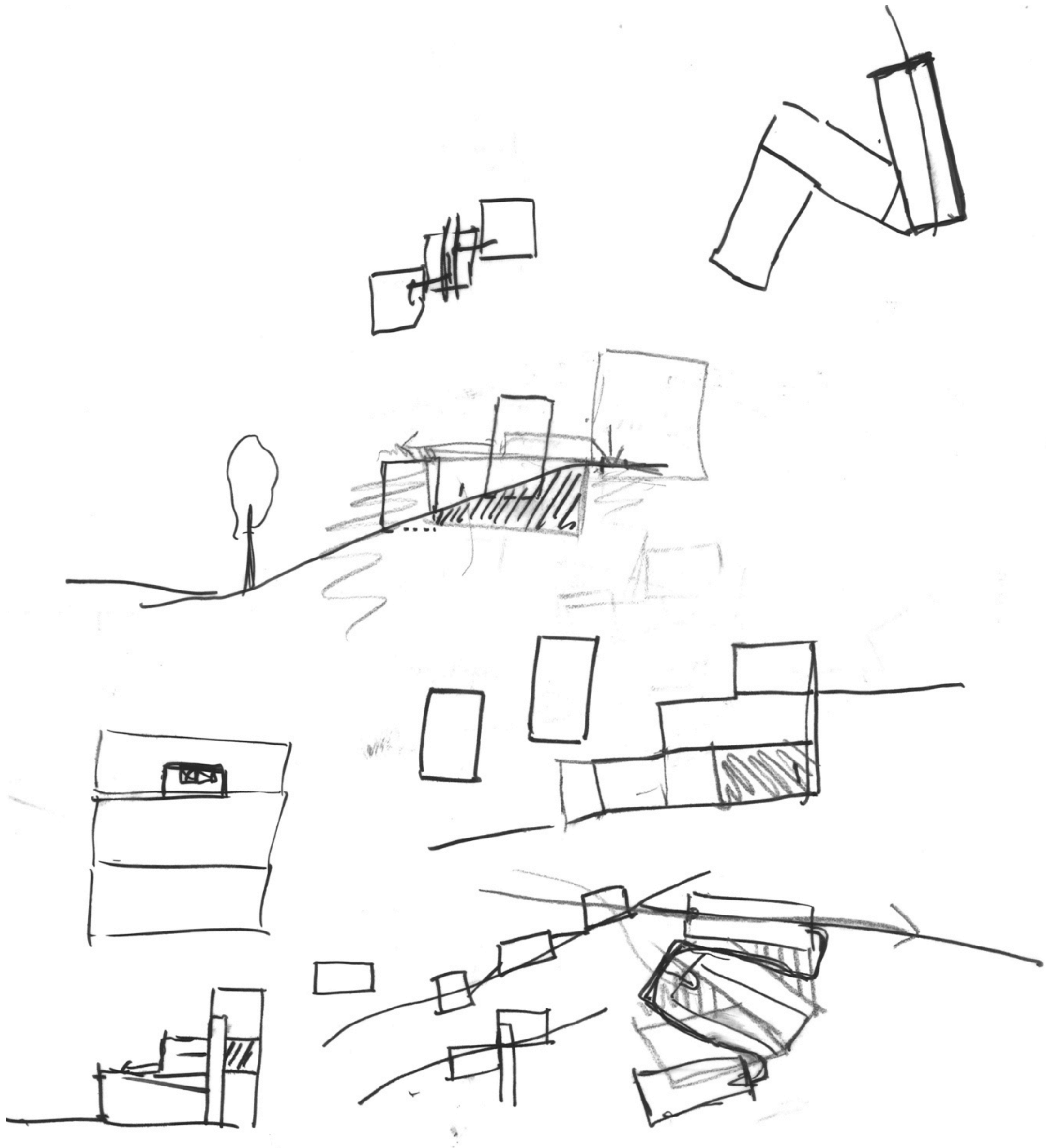


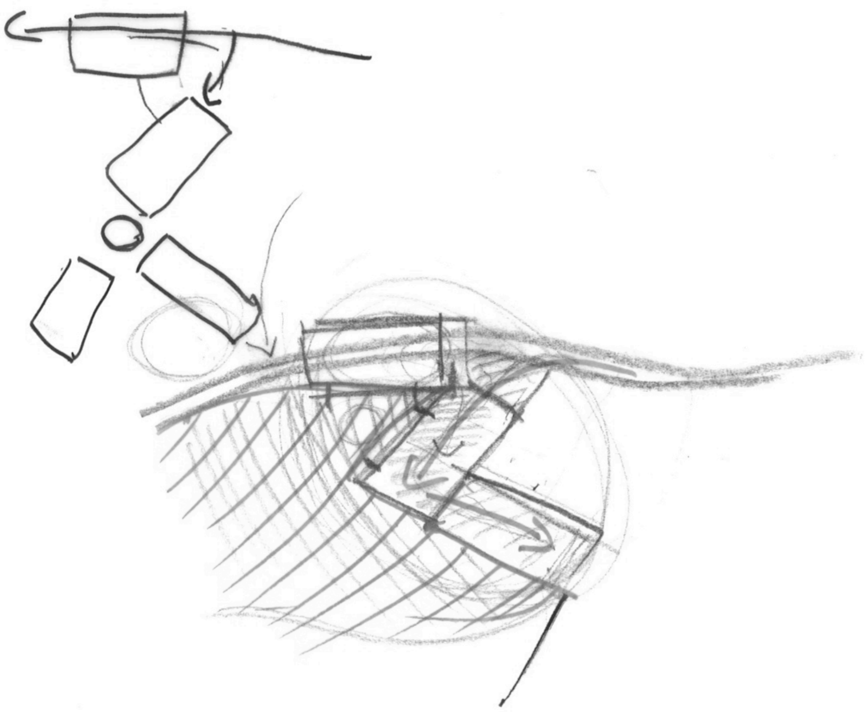
Presentation of the final concept proposal

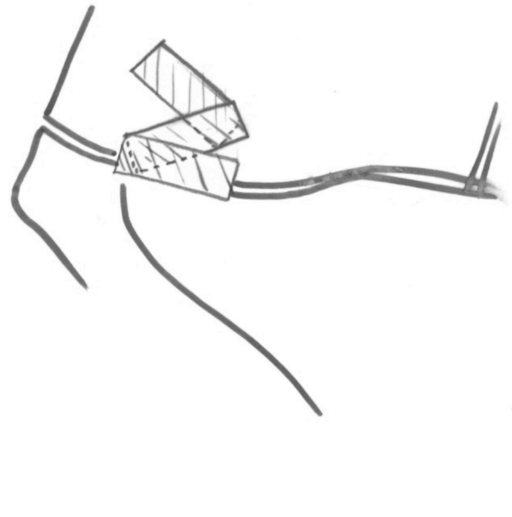
Discussion

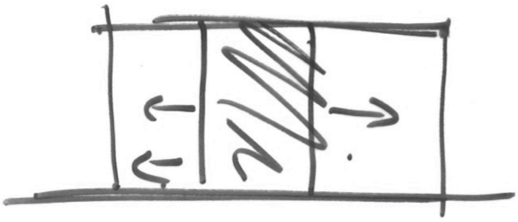
- **What do you think of the multidisciplinary collaborative design?**
- What are the concepts you explored?
- How did you explore them? Which was your process?
- How do you evaluate the solution?
- How did the Protocol assist the design process?
- Which moments were creative?
- What did you think of the provided means? (i.e. The Surface App, the laptop, analogue means, etc.)
- Any further suggestions for the Microsoft Table?

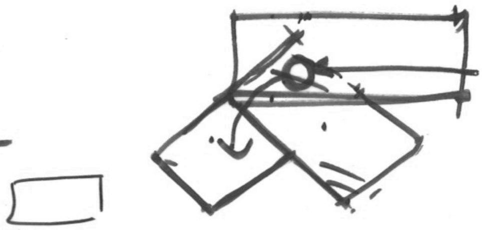
4. Participants sketches and notes

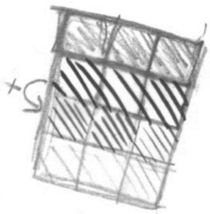


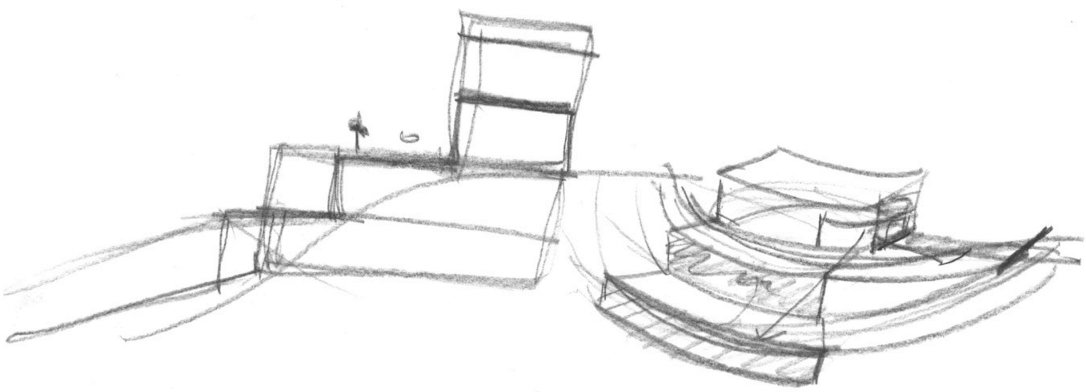


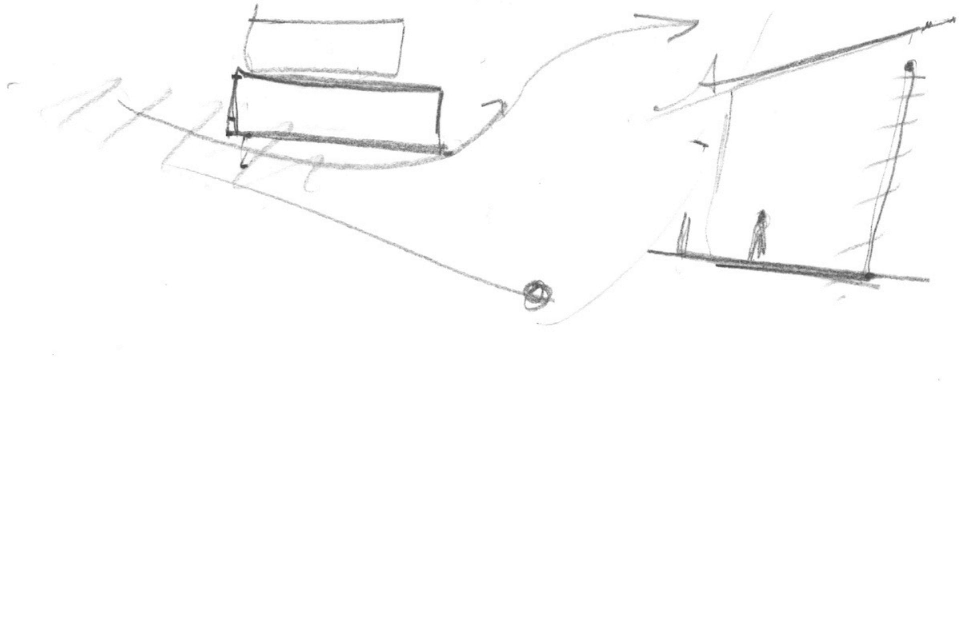










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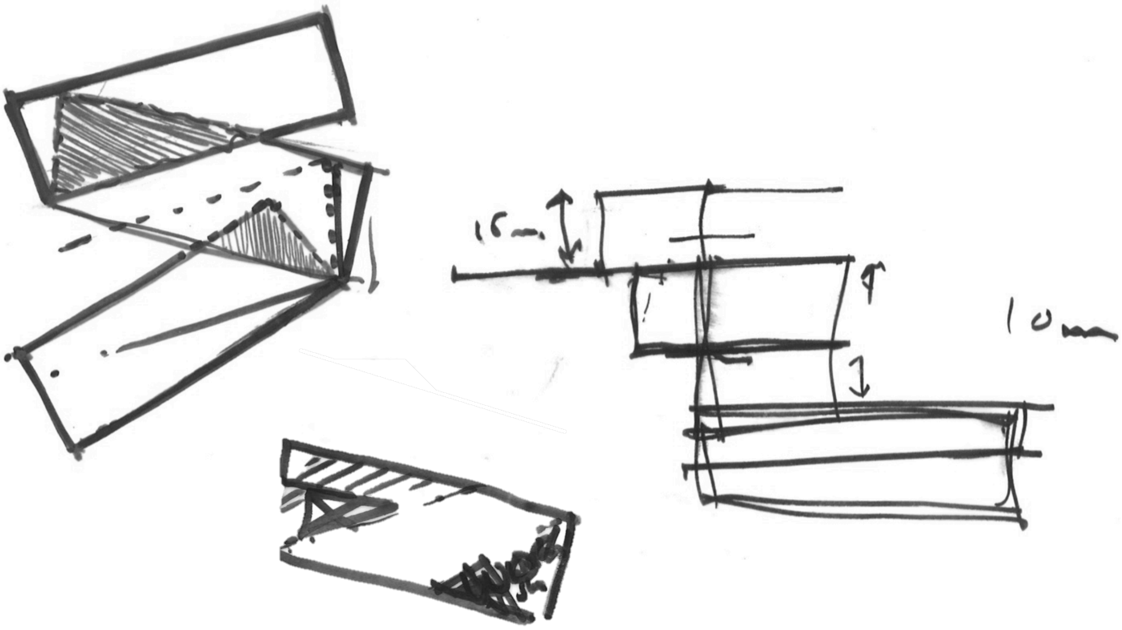
Kaim Cottage
Path
Path
Lodge
Scott Sutherland
School of Architecture
School of Surveying
Garthdee House
Path



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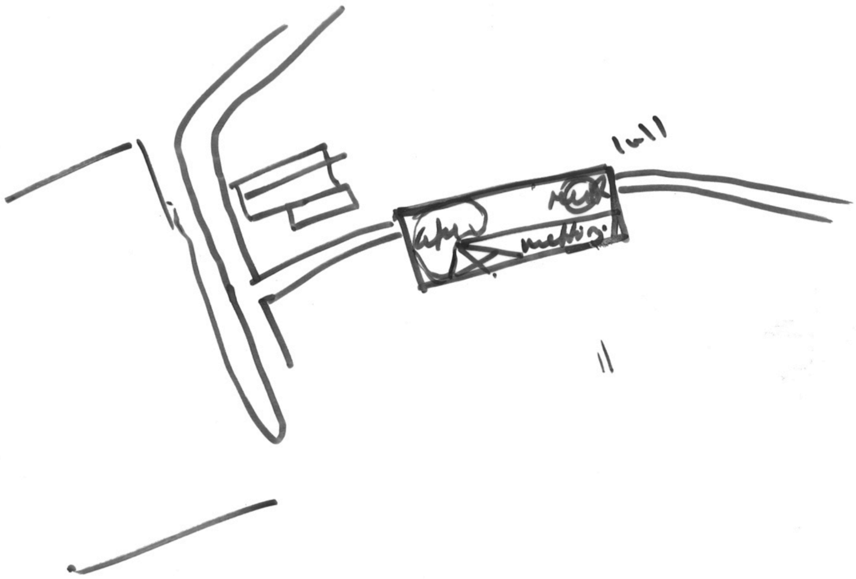

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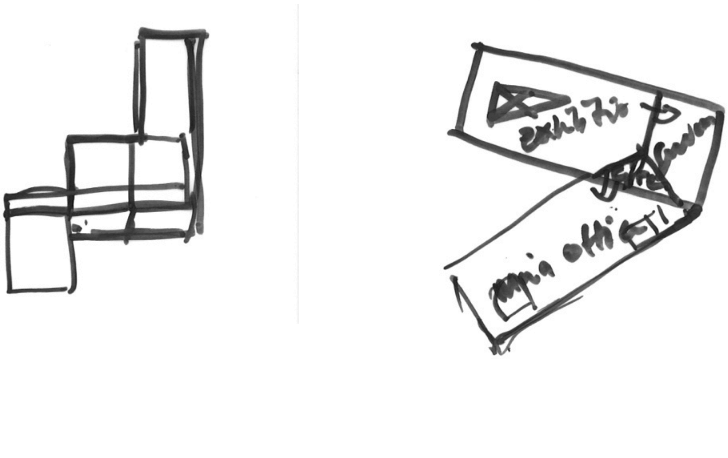
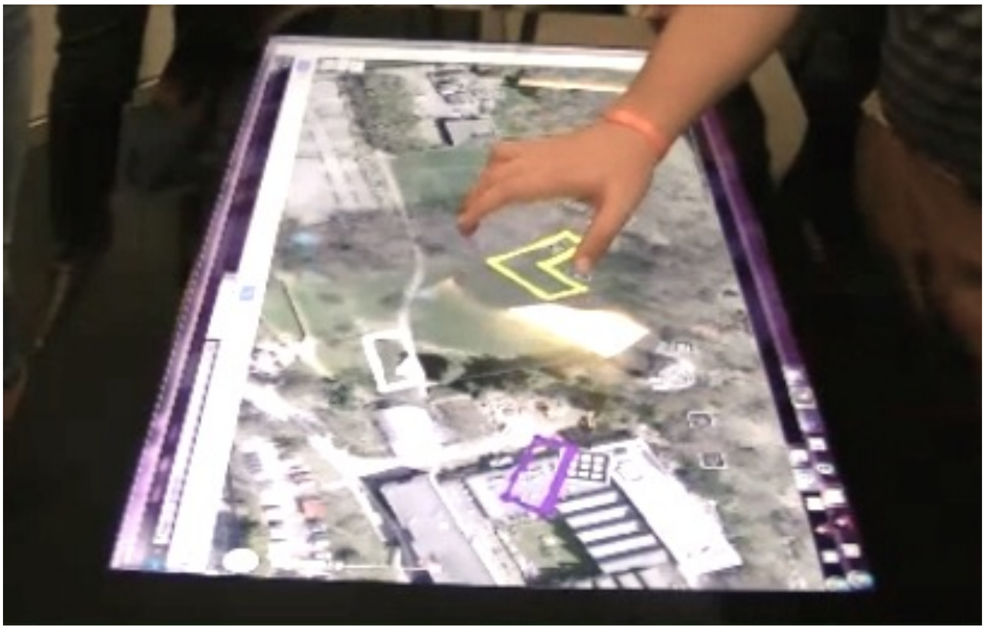
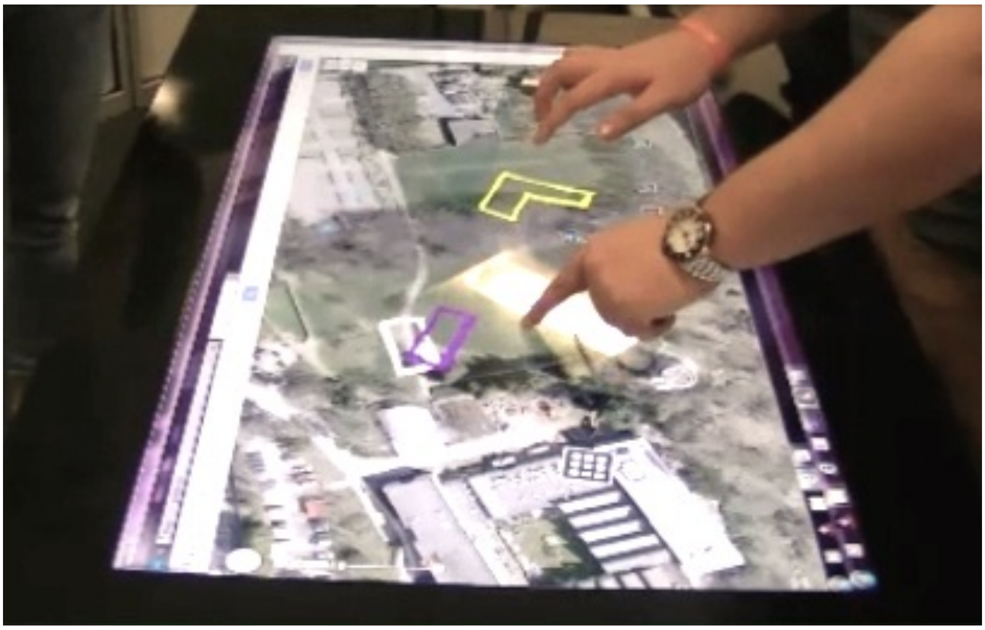
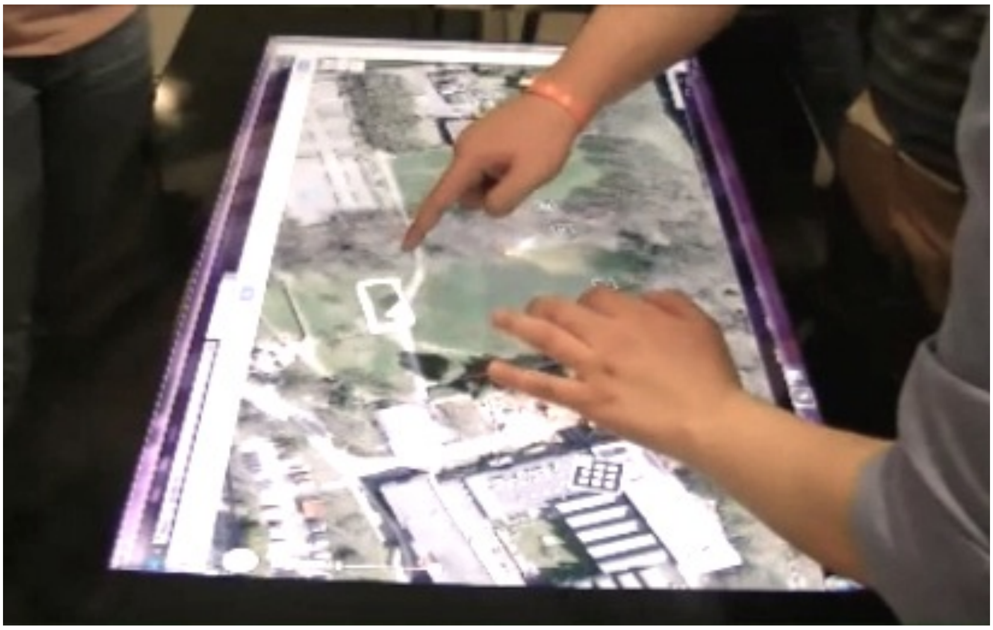
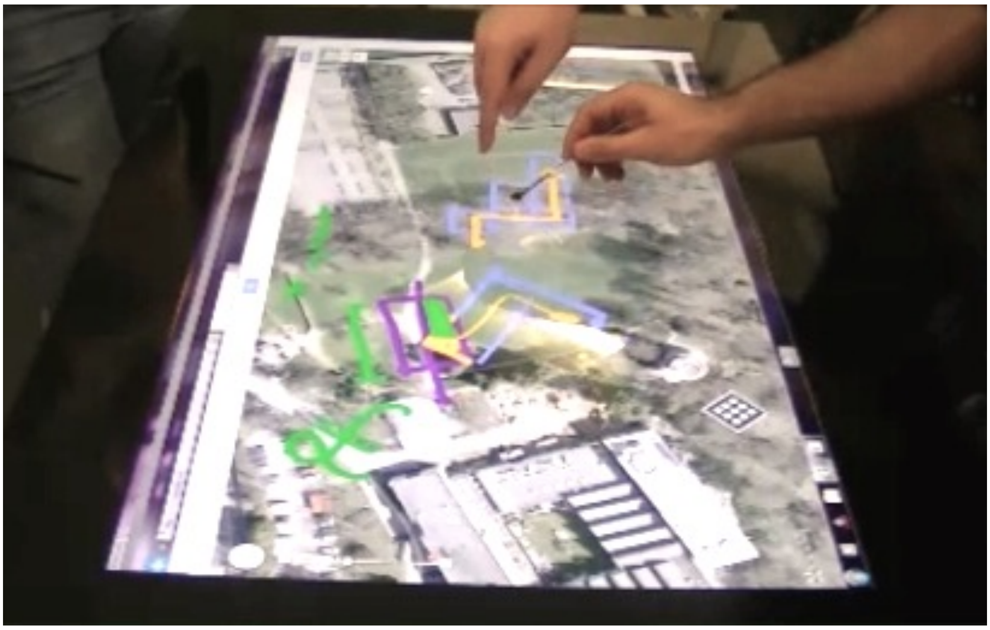
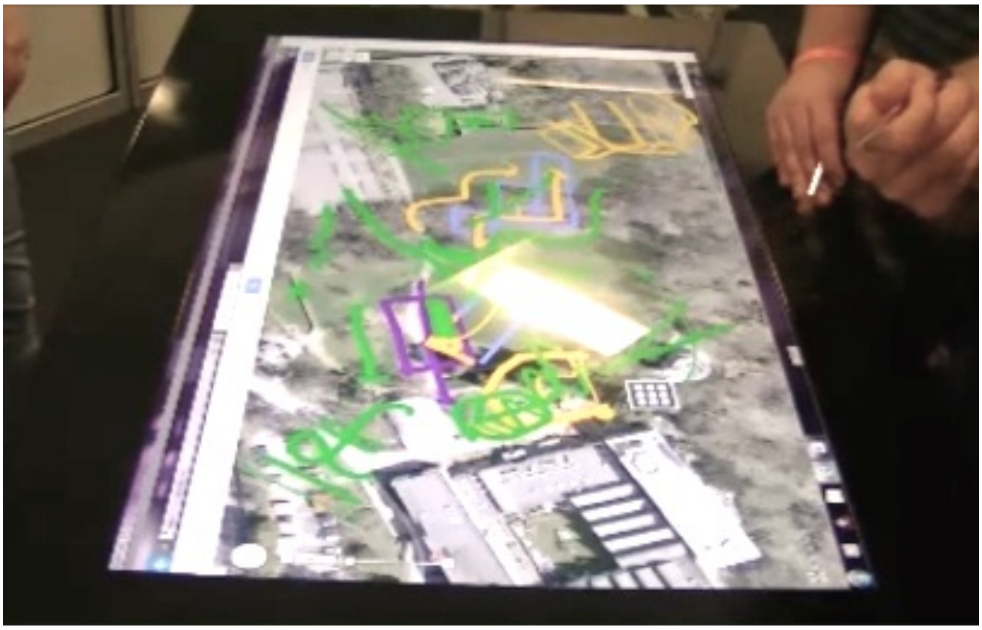






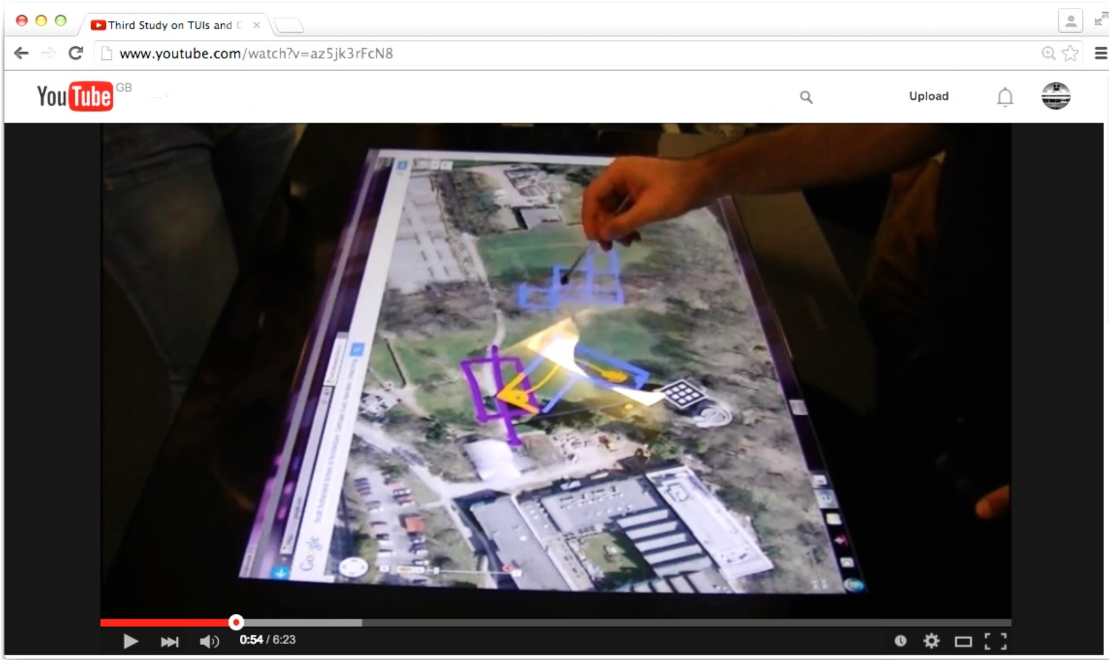






5. Youtube Link:

http://www.youtube.com/watch?v=az5jk3rFcN8



Appendix G: Publications

- Leon, M., Laing, R., Malins, J., & Salman, H. (2014). Developing a design protocol for computer mediated collaboration during the concept stages with application to the built environment. Procedia, Science Direct, Elsevier, 12th International Conference on Design and Decision Support Systems in Architecture and Urban Planning, DDSS 2014, Eindhoven. http://www.sciencedirect.com/science/article/pii/S1878029614001583

- Leon, M., Doolan, C. D., Laing, R., Malins, J., & Salman, H. (2014). Application of interactive surfaces to support computer mediated collaborative design environment. Proceedings of the 18th International Conference on Information Visualisation (IV and BuiltViz), Paris, France. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6902916&tag=1

- Leon, M., & Laing, R. (2014). Application of conceptual stages design protocol for early collaborative design through computer based mediation. 2014 International Conference of Architectural Technology (ICAT) Conference, Aberdeen, UK. https://openair.rgu.ac.uk/handle/10059/1154

- Leon, M., & Laing, R. (2013). Cloud and computer mediated collaboration in the early architectural design stages: A study of early design stage collaboration related to BIM and the cloud. 2013 IEEE 5th International Conference on Cloud Computing Technology and Science (CloudCom), 2. pp. 94-99. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6735402

- Leon, M., & Laing, R. (2013). Towards a computer mediated methodology for collaborative design during the early architectural design stages. Proceedings of the 2013 IEEE 17th International Conference on Computer Supported Cooperative Work in Design (CSCWD), pp. 489-495. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6581011

- Leon, M., & Laing, R. (2012). The review of BIM as an effective tool for collaborative design during the early design stages. Proceedings for the First UK Academic Conference on BIM, pp. 109-117.

- Leon, M. (2012). BIM and collaborative design as effective tools for sustainable healthcare refurbishment during the early re-designing phases. CIC Start Conference, Sustainable Refurbishment of Healthcare Estates, Glasgow UK. (Invited Presentation)