

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. Developing the Design Protocol

2.1. Design protocols review

The design processes have been modeled according to different perspectives and theories, either applied from Architecture, Engineering and Construction (AEC) practice based perspectives, like Royal Institute of British Architects (RIBA) Plan of Work³, Construction Operations Building Information Exchange (COBie) Data Drops⁴, British Standards 7000 Part4⁵, etc. design field^{6,7} or from engineering perspectives^{8,9} etc. 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 (Fig.1). 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 development⁷. If there are problems within this process, feedback loops lead to the generation of new concepts and the design process starts again.

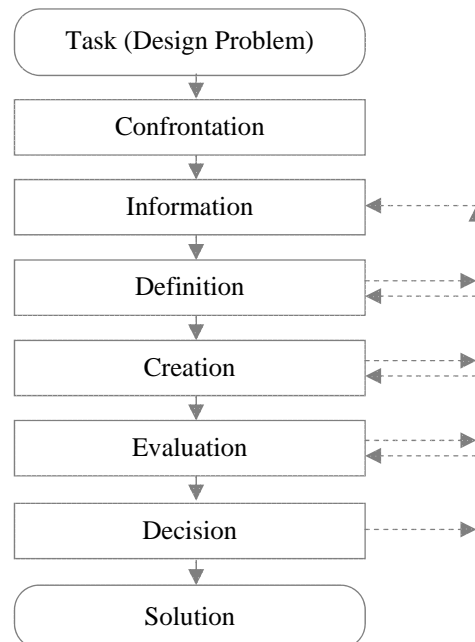


Fig. 1. General process for solutions' finding.

The described design process 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. Schön's theories on reflective practice for design practitioners provide the most basic form of design process, which is the four successive steps of identifying and naming the design problem, framing and reflecting on the decision and reaching the end result⁶. 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 Beitz⁸. These stages include conceptualizing 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^{8,10,11}. The key stages from design and engineering disciplines

are presented in Table 1. These links can effectively achieve a generic framework for solutions finding as illustrated in Figure 3. The latest and most important practice focused design processes are also presented in Table 2.

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.

Table 1. Design and engineering field conceptual design processes

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 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 2. Practice-focused initial and conceptual design systems

Initial Design Stages			
RIBA Plan of Work 2013	1. Preparation: Project Objectives, Business Case, Feasibility Studies, Assemble Project Team, etc.		2. Concept Design: outline design proposals (structural, services, landscape), preliminary cost planning, Agreement on Project Brief, etc.
PAS 1192-2:2013	Brief	Concept	Definition Design
COBie Data Drops 2012	Data Drop 1: Requirements and Constrains	Data Drop 2: Outline Solution	Data Drop 3: Construction Information, Data Drop5&6
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

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 respectively BS 7000-4:1996 on design management systems and BS 1192:2007¹², which is the 'Code of Practice' for CAD and includes information on BIM design workflows and levels of adoption. The details of these design processes are briefly presented in Table 2.

2.2. Proposed pre-defined design protocol

The design systems considered in the research result in proposing a predefined design protocol, following the lack of an organized system focusing solely on conceptual stages, especially within built environment industry.

Interestingly enough, 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, 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 organized 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 understanding¹³.

Based on that research, a predefined design protocol has been developed and tested during two case studies. 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 taking account of 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 (Fig. 2). The Conceptual Design Protocol, as a simplified process applied for the built environment, initiates 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.

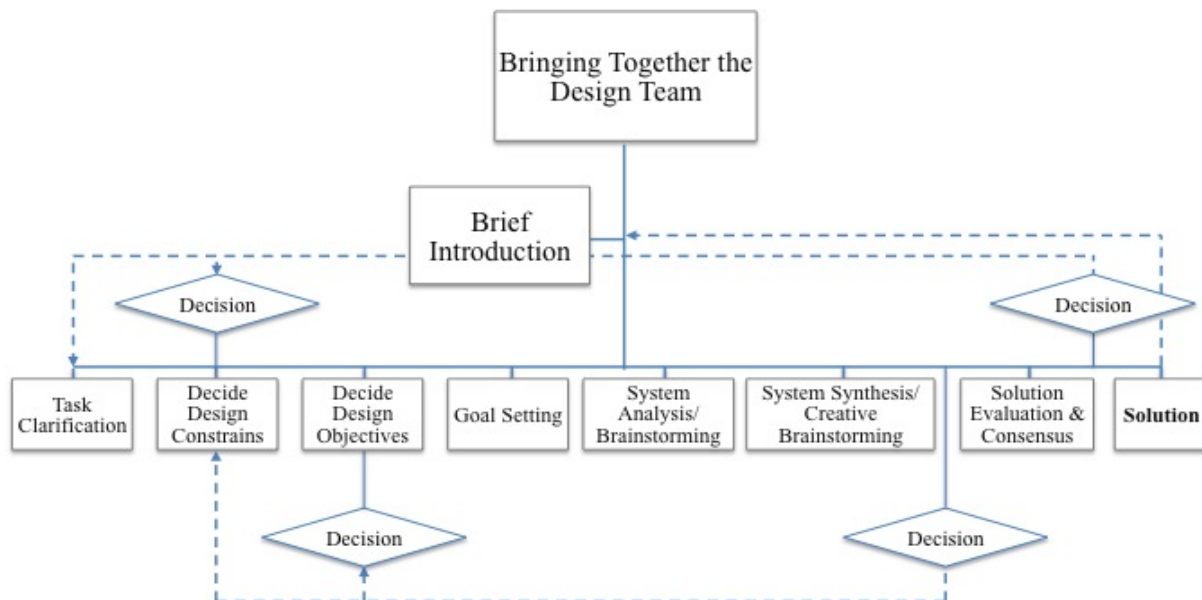


Fig. 2. The pre-defined design protocol for the conceptual design stages.

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, other buildings examples, etc. 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.

3. Studies

3.1. Studies description

Collaborative design processes during feasibility and concept stages have been tested during two experimental studies, involving multidisciplinary design teams that developed a design concept for an educational office building. The participants in both studies were design professionals with experience in Architecture, Engineering and Construction (AEC) industry, including two to three architects, a quantity surveyor, a building surveyor, a structural engineer and a construction manager, with different combinations of these in both studies. Furthermore, the design brief in both studies was about a conceptual design solution for a small educational and research building while a study moderator was taking them through the task introduction in both studies and was making sure that the team was following the pre-defined design protocol during the second study.

The resources and media available to the designers during the studies were those widely used in professional practice. These included tracing paper, markers and commercial design applications (see Fig. 3). In addition to that, a Microsoft Surface Table with Microsoft® PixelSense™ (M.S. Pixelsense) was used, which is a Tangible User Interface (TUI). M.S. Pixelsense is a vision based multitouch system and infrared sensing that allows for fifty two concurrent interactions, thus enabling experiments on computer mediated collaboration through visual and tactile user interfaces. A key difference between the two studies includes the computer-mediated design aspects. During the first study, the participants utilised the M.S. Pixelsense with off-the-shelf commercial design software (drawing application and Autodesk Sketchbook Designer). A usability report informed about 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. The developed software was used during the second study and it included a small repository of operations, aiming at natural drawing process. The 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, etc.



Fig. 3. Typical studies' setting.

The conceptual design activity was monitored and mapped in both studies for the purpose of understanding the design process adopted by the design team. The first study is exploratory, in which the professionals followed an unstructured conceptual design process in order to provide a comparison with existing studies focused on conceptual design protocols⁶. The following study applied the design protocol during the conceptual stage, making use of a managed facilitation process throughout the design project.

The design progression patterns of the two 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. Importantly, the creative and unexpected users' interactions with the physical means of exploring ideas during the second study, led to a merging of physical and digital worlds, which further promoted a

vibrant collaborative design process with more extensive interactions between the participants. Moreover, discussions at the end of each study demonstrated in greater detail the designers' ideas and opinions on the design process and further supported the arguments for multidisciplinary and computer mediated collaboration.

3.2. Protocol analysis and activities mapping review

Protocol analysis and activities mapping are the preferred methods for analysing studies results. The particular methods have been used extensively for analysing studies focused on design problem solving, on design cognition (14, 15), on designers' collaboration and interactions with computer mediums^{16,17}. Further research on mapping the design activities includes conceptual activity of interdisciplinary teams^{18,19} and comparison of engineering and construction design stages²⁰.

Three distinctive approaches to analysing the studies data have been identified. To begin with, the macroscopic analyses of design processes of architects as presented by Gero¹⁴ 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 divided according to different types of categories, which depended on the perspective of the analysis. Gero 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 are categorized accordingly. As a result, different kinds of relations among the design actions could be identified and correlations between different actions were also feasible, as shown in Figure 4 and 5.

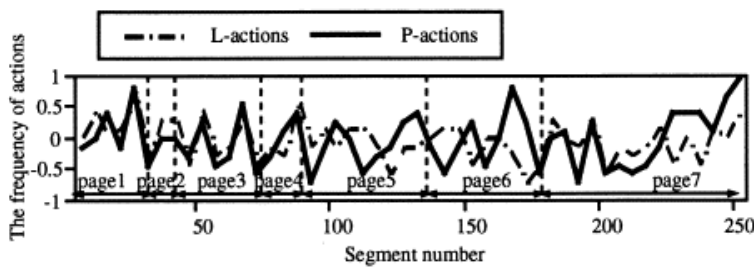


Fig. 4. Correlations between perceptual actions (P-Actions) and looking (L-Actions).. Gero¹⁴, pp. 477

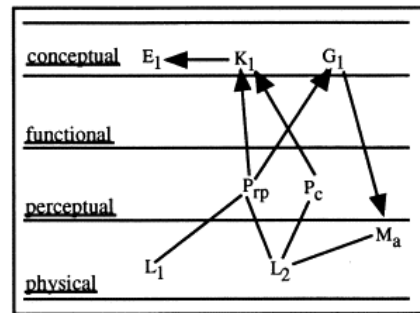


Fig. 5. Relations among design actions for a segment Gero¹⁴, pp. 471

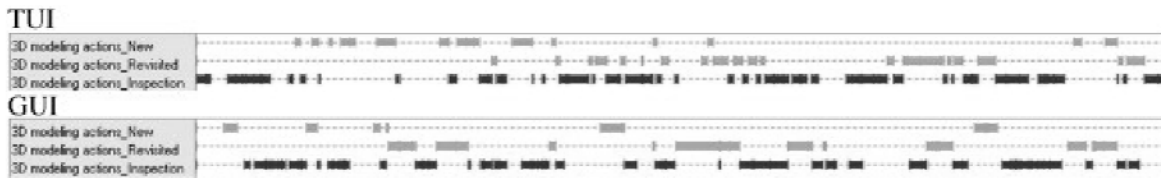


Fig. 6. 3D modelling actions according to time spent on each level¹⁶, pp. 276.

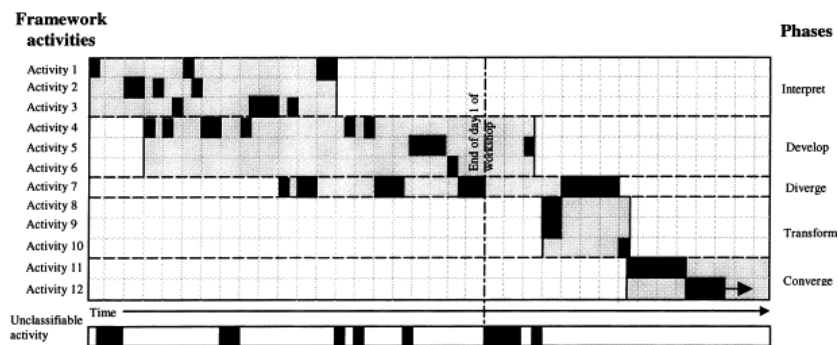


Fig. 7. The design activities outline according to time spent on each of them¹⁸, pp.216

Likewise, protocol analysis steps as described by Gero and McNeill have been adapted by Gu et al.¹⁶ 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 categorized according to four levels, the collaboration level, which includes cognitive synchronization, perceptual level for perceptual activities, the action level for modelling actions and the process level for setting up goals. The authors analysed the designers' behavior 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 (Fig. 6).

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 professionals¹⁸. The studies included three test teams that were called to design a building element, a modular window system. The studies' stages were recorded by the actual participants as the studies were being undertaken and the segments were categorized according to a conceptual design protocol that was developed before the studies²¹. 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 (Fig. 7).

The common characteristics of all design processes analyses 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.

For the aims of the research presented in this paper, protocol data utilised for analysing the studies consist 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 thinking²², like sketches drawn from the participants, excel spreadsheets with their calculations and information found on the Internet. It is also essential to make a clear distinction between the protocol data from the monitoring activity and the pre-defined protocol, which consists of given steps and iterations for the participants to follow. The analysis is focused on participants' physical actions, on perceptual and conceptual actions and on collaborative processes according to the steps presented in Figure 2. As a result, a map of the conceptual activities is created for the purpose of showing the design protocol in both studies, for providing insights in order to understand the processes that the design teams are following and for presenting the levels of adaptability to the pre-defined protocol. Further details on the usability aspects of the computer mediums and the application of TUI adapted design software can be found in previous publications^{23,24}.

3.3. Studies structure

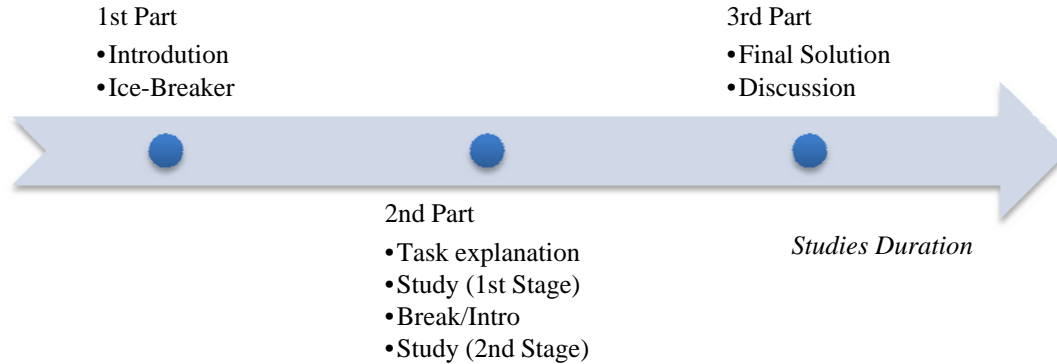


Fig.8. Studies structure

Both of the 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 [25]. The particular time slot was lasting for twenty minutes approximately. Afterwards, the task explanation followed and the first stage of the actual design process initiated, again within certain time duration of an hour and a half. A short break worked as an introduction to the TUIs that they were called to use for the second stage of the study that was lasting forty-five minutes, during which they were called to further develop their ideas by using the computational mediums. The last part of the studies included the presentation of the conceptual design and a short discussion with the participants on the process (Figure 8). The analysis is focusing on the development of the conceptual design and the steps that the participants are undertaking to reach the conceptual solution and complete the preliminary feasibility stage..

3.4. First study results

Avoid 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 (Table 3). 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 called to design. Furthermore, they were given specific time slots for completing their overall task. During the first study the participants did not have any guidance or they were not provided with any walkthrough for tackling the design task. Their design process mapping is analysed according to the generic design protocol steps presented in Figure 2.

From the start 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 (Fig. 9). The leap led to a series of iterations between brainstorming and analysis while the lack of particular objectives and constrains 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

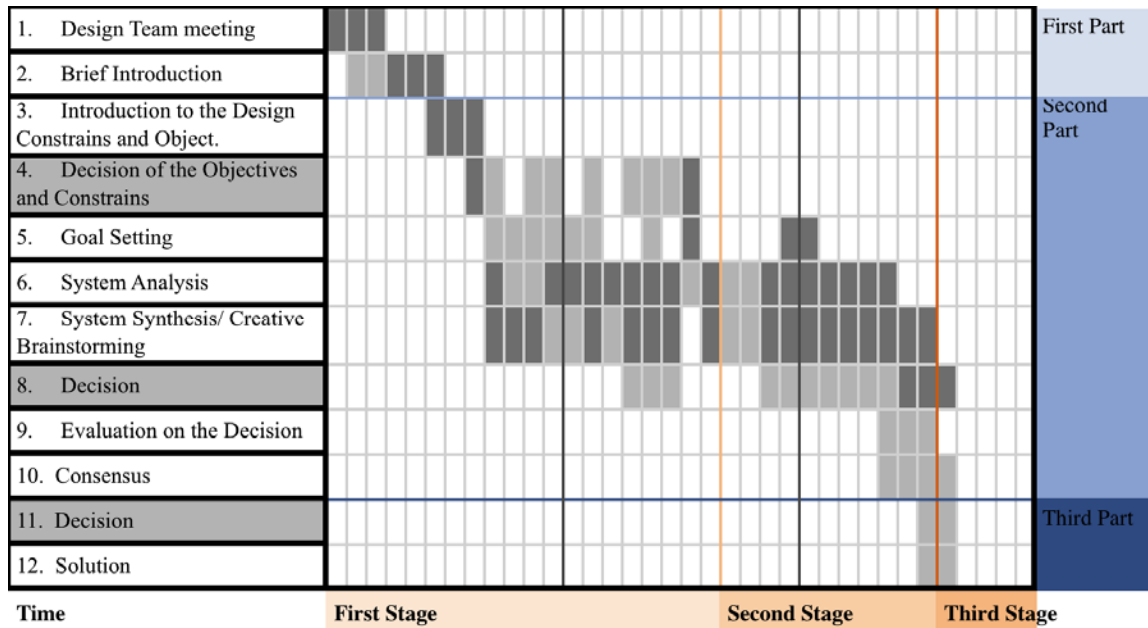


Fig. 9. The design activity during the first study. (The dark areas highlight the main activity while the lighter ones parallel and secondary activity).

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 called to use the TUI to continue 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 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. 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.

After the conclusion 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 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.

3.5. Second Study results

The second study shared the same structure with the previous one, even though this time the team members were called to utilise the conceptual design stages pre-defined protocol (Fig. 10). The design brief this time included further information on the requirements making the task more complicated than the first study. During the introductory first part the relevant 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 on objectives and constrains straight from the beginning of the design process, thus following the pre-defined protocol. The fourth step, which was deciding on the objectives and constrains, 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 on details of the project, like the form, decisions on types and volumes of space, deciding about budget and its effects on the concept, were also finalised during that stage.

The professionals were called 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 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/constrains/aims between the professionals was achieved earlier on. During the discussions they were also reflecting on their own professional experience, other similar examples of buildings they had designed or they had been advisors to or similar type of buildings they had experienced themselves.

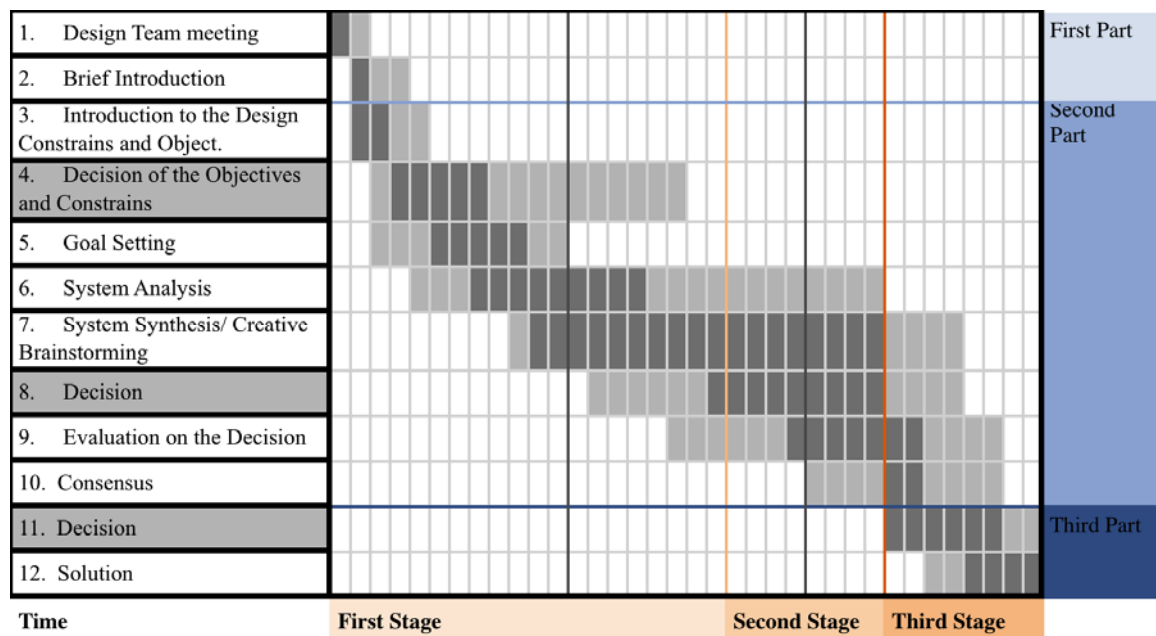


Fig. 10. The design activity during the second study. (The dark areas highlight the main activity while the lighter ones parallel and secondary activity).

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 manage 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 realized 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.

4. General Discussion

This paper involved two case studies of multidisciplinary professionals who were asked to complete a conceptual design of a small building by utilising both physical and digital means. The participants had a similar level of expertise in both studies, in order not to affect the end result. Additionally, the process they followed and the available design software were different in each study. By comparing the two graphs that map the design process in each case, a number of conclusions can be drawn. First of all, it is obvious that the process in the first study lacked cohesion and the design task was not completed, the end result was a rather abstract selection of ideas. The second study, not only saw the task being completed in time but also had successfully tackled the design problem/brief by producing a quality solution. What is more, during the second study the updated software installed on the TUI assisted in having them focused on the different types of relations between the building elements more effectively than the first study, thus allowing for a smooth continuum of the design protocol. The reason being that the developed design app managed to draw users' attention on the screen, like the first study, but also assisted for a more intense ideas exchange among them and had them situated around the Pixelsense, drawing smoothly while actively participating in discussions.

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 provide insights in the nature of multidisciplinary design process and show the effectiveness of the pre-defined design 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.

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