A Digital Incorporation of Ergonomics into Architectural Design

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A project that is particularly designed for digital studio settings is described. Facilitated by multiple computer modeling and animation software, the project incorporates concepts and applications of ergonomics and kinetics as two ingredients and concept generators with problem-based learning techniques into architectural designing. Reflections about the project and its outcomes are reported and discussed. The results indicate that considerations of ergonomics, flexibility, mobility and responsiveness in dynamic structures and their interactions with users can enrich and optimize generated designs. Similarly, the application of problem-based designing approach seems to foster critical thinking of participants and improve their involvement in collaborative design processing.

1. Introduction

Kinetic, interactive and growing architecture are relatively new areas of focus within architectural design practice and education. Command of design in these areas requires new competences and skills. The additional skills needed to generate four-dimensional animated and mutational compositions, and to master "imagineering" in conceptual formation must be enhanced by high imagination and creativity as well as adequate technical knowledge of the proper tools to communicate morphing shapes and their transformations. Generating such compositions poses challenging design problems and puzzling settings for designers. Fortunately, advances in the relevant fields of knowledge facilitate solving such problems. On the one hand, computer hardware and advanced animation software are now available to facilitate the production of virtually transformable and alive designs. On the other hand, new learning methods are proposed to facilitate hands-on interactive learning for practice-oriented professions. Moreover, scholarly interests in trans-disciplinary knowledge mobility are increasingly highlighting new areas of research that address potential synergy of different disciplines to enrich design processes and products. Despite these advances, current design methodology and pedagogy in most schools of architecture do not focus on such complex design concepts. For designers to understand the principles of movable structure, an introduction to active hands-on learning strategies seems essential. A traditional unstructured trial/error -based approach to design is not the best way to enable students to visualize animated three-dimensional morphing designs. This paper describes a pilot four-week project that addresses the kinetic and interactive architectural structures. The project was devised for third year design students from the school of architecture at Jordan University of Science and Technology (JUST). It is an experimental project that incorporates emergent design concepts about ergonomic-based and animated n-dimensional design and visualization methods into a problem-based learning approach that is carried out in a digital architectural design studio. The pilot employs computer aids not only to integrate different data, present ideas and to communicate online, but also to emphasize concepts that are typically considered difficult to visualize in design derivation and representation such as responsive metamorphosis of spatial organizations. Reflections about the application of the new concepts, pedagogical experiment and project implementation are presented and discussed in the following sections.

1.1 Ergonomics in architectural design

According to the International Ergonomics Association (IEA) [1] ergonomics- human factors or human-centered design- is defined as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance." Ergonomics is typically classified into Physical, Cognitive and Organizational areas. This first is concerned with the physical aspects and measurements of human body. These include the anatomical, anthropometric, physiological and biomechanical characteristics that are associated with human physical activities. The second is concerned with the mental processes, such as perception, cognition, memory, and reasoning that are associated with the interactions among humans and artificial products. The third is concerned with the optimization of the organizational structures, policies and processes of product systems [1].

In the context of this paper, the overall system mentioned in the definition above is interpreted as the built environment that directly surrounds humans, and the goal of ergonomics application is defined as optimizing human-building interactions. While all categories of ergonomics are significantly influential on architectural design, the main type of concern here is the physical ergonomics. Within the scope of this paper, the ergonomic approach may be defined as the extrapolation of future expected scenarios of post-occupancy user interactions with spaces to existing setting analyses of pre-design spatial planning in order to optimize design of buildings in terms of quality, functionality, behavior and comfort of users. The future predicted scenarios are usually combinations of event-based scenarios and potential end-user circulation and behavior simulations.

Ergonomics is usually associated with anthropometrics. The latter is mainly concerned with the measurements of human body and their impacts on product dimensions, scale and proportions. While anthropometrics affects mainly the static settings of product designs, ergonomics add time and motion considerations. It enhances the basic anthropometrics-based engineering design with health, comfort, fun and efficiency and even entertainment considerations.

While applications of anthropometrics and ergonomics in industrial, automotive, computer and mechanical engineering design areas and even in interior design are well-established, examples of the consideration of ergonomics as a design generator or catalyst in architectural design derivation are very few. Most of these efforts focus on healthcare facility design [2, 3] and working environment or office design [4, 5, 6, 7]. Even in the few existing scholarly efforts of ergonomics-based design [8], the area of incorporating ergonomics principles into the early phases of design schematic planning, programming, processing and conceptual formation is considerably under-researched.

1.2 Problem-based learning approach to design pedagogy

Since its introduction in the 1960s, Problem-Based Learning (PBL) has become a common way of instruction in higher education of practice-oriented professions [9, 10, 11]. It has become widely used across some areas such as medicine, languages and engineering. PBL was initially developed in response to concerns that the conventional subject-based approaches to teaching did not provide the most effective training for future professionals who needed to access knowledge across a range of disciplines and in realistic settings [12]. PBL can be described as an educational format that simulates real life practice settings through pre-defined problem scenarios in order to encourage the discussion and learning of the experiences that emanate from practice-based problems. It is a method that fosters independent learning, encourages students to practically tackle perplexing situations and actively define their own gaps in understanding the problems in their realistic contexts, and enhances a more comprehensive as well as deeper understanding of the material at hand.

The PBL approach can be characterized by being integrative, collaborative, top-down, whole-to-part, practice-oriented, teamwork-oriented, student-centered, process-focused, problem-focused, hands-on, customized, flexible and interdisciplinary [13]. In addition, it encourages independency, creativity, and self-initiation, and strengthens problem-solving and active learning skills. PBL reverses the traditional approach to teaching and learning which is generally bottom-up or part-to-whole. In the conventional approaches, learning starts with different subjects, knowledge components or puzzle pieces to incrementally arrive at the final products, experiences or assembled puzzles. In contrast, PBL starts with whole cases or problem scenarios that stimulate practice settings. In a deductive analysis of these settings, students arrive at general principles and concepts underlying the cases or scenarios which they then generalize to other similar situations. A desirable attribute of problems used in PBL approaches is that they are preferred to be 'ill-structured' [14]. In this regard, Jonassen [15] distinguished between ill-structured and well-structured problem applications. The settings of well-structured problem may have 'right' and 'wrong' answers and can be introduced to guide students to demonstrate simple rules, concepts and procedures with information gained from direct sources. In contrast, ill-structured problems pose complex and real life problems for which the "right" solutions cannot be found in direct resources [16]. Most architectural design problems can be considered ill-structured. The general attributes of practice-oriented, ill-structured, multi-disciplinary, and multi-layered aspects of architectural design problems that correspond to those in PBL definition seem to qualify PBL instruction to partially replace or enhance current design tutoring methods.

2. An ergonomics-driven design project

Based on a premise that weaving ergonomics, kinetics, PBL and computer visualization aids may produce an effective systematic building designing method, students of the digital design studio in the school of architecture at (JUST) were assigned a project entitled: anthropometrics- and ergonomics-based house. In this project, students of third year level were asked to design a house that integrates ergonomics (human interactions with artificial products) and anthropometrics (the measurements and proportions of human body) into architectural design. This approach to design was coupled with problem-based learning methods to improve students' productivity and gain from the project. In this project, students were required to design a house for a family with special needs. It consists of a tall professional man (architect), a short wife who owns a home business (preparing deserts and delivery meals upon request), an elderly grandmother whose hobby is gardening, and a handicapped artist son who likes painting. The land plot is small (15m*20m). The family has some knowledge about ergonomics and it–as a client of each student- wants student's virtual architectural office to design the family's house. The family wants their house to meet their special needs according to principles and guidelines of ergonomics. Students were required to consider the requirements concerning each user's circulation patterns and experiences within each space and during transition between different spaces. The students have to derive these requirements from studying all possible scenarios about each user's behavioural tendencies and movement patterns. Students have to solve any predicted conflict in users' interactions. The user behavioural information was encouraged to be structured in process flow diagrams, hierarchy charts, and computer animated walkthroughs that simulate each user's experience in the spatial organization of the proposed house from his/her perspective and viewing from his/her eyelevel and height measurements. As such, the adjustments of each element in the built environment surrounding each user to his/her changing needs throughout a long period within the lifecycle of the house as dealt with by ergonomics were supposed to be presented digitally.

In this project, the main concern was not the finished product – house, but rather how to ergonomically initiate and sustain the design development process and manage the different activities that are associated with the space creation and connection with other spaces and systems within the larger framework of the house's context and environment.

An essential catalyst of this design was its responsiveness to considerations of the changing needs of the family. In all growth phases of its life cycle, the house was supposed to respond in function, size, settings and accommodations with dynamic structures that are easy to modify, assemble and dissemble to the needs of each family member. Solutions should consider issues such as dynamic new structural systems, flexible furniture design with multi-use settings, and adaptive supportive climate-sensitive environmental control systems. In addition to the house structures and systems, the flexible multi-use furniture pieces were supposed to be designed according to principles of anthropometrics and ergonomics to ensure optimum functionality and user-furniture interactions. For example, the kitchen was required to be designed to fit the short wife's measurements and the very tall husband's scale. This could be achieved, for example, by adjustable counter and sink the height of which may be altered for each user using sliding tracks.

For this project implementation experiment, 16 students were divided into groups of four to design the ergonomics house and present it animated throughout all its lifecycle phases. The house was required to be considered four-dimensionally where the time element and motion considerations were added to enhance the typical spatial three-dimensional model to illustrate all changing needs and growing states of the house's life cycle. Design parameters regarding size, style, structural and technical solutions were free. However, the following stipulations were required to be adhered to:

- Within all scenarios of house adjustments, building and environmental control systems should be integrated with the spatial organization and should move in accordance with each other.
- Space sizes should be kept to optimum for each phase of the house's life cycle.
- All furniture pieces should be dynamic and flexible to fit into different functions and phases.
- Transition from a state into another should be accomplished with minimal physical effort.
- Mantling and dismantling should be made as easy and quick as possible.
- The amount of structural change that responds to a change in the family needs should be kept to minimum.
- Cost efficiency is not critical in this project. However, economy should be considered when choosing from alternatives.
- The colour scheme and interior design should respond to the psychological changing needs of the family members.
- An animated multimedia-aided presentation is required to animate each member's experience in the house.

Designing this adaptive house and solving the problems associated with its predicted adjustment and responses to users' needs aimed to achieve multiple objectives**.** During the process of design derivation, students were expected to:

- Learn new design methodologies
- Explore the role of ergonomics as new design concept, function and form generators
- Develop explicit design processes that are customized to each student's pace
- Strengthen critical and analytical thinking and techniques
- Experiment with new ways of representation
- Employ multi-media tools and aids

- Experiment with new styles of learning
- Apply emerging concepts of design from different disciplines
- Investigate principles of ergonomics and explore their impacts on architecture
- Integrate knowledge from multiple disciplines
- Manage teamwork and enhance communication skills

Within a timetable of four weeks, students were required to start the project in a collaborative teamwork investigation of relevant information. Within each team, they were assumed to divide the work and communicate on-line when not physically in the studio. They applied external referencing of initial concept presentations to integrate their efforts and update their designs with the latest adjustment any member of the team may come with. The project pre-design phase was designed to be conducted in two week team work collaborative pre-design data collection and analysis and study of predicted scenarios of space utilization for each user. Each team member was expected to digitally simulate all expected scenarios of one of the four users of the house. Students within each team then exchange the predicted scenarios to understand variations in experience and use of spaces for the house users. By the end of this pre-design phase, students in each team were expected to suggest design recommendations and solution alternatives based on their collaborative research and reasoning. This stage was then followed by two week individual development of design solutions where three-dimensional models are generated and evaluated internally and externally in animated studies that investigate how each family member will experience the designed house four-dimensionally.

3. Problem-based ergonomic approach to digital design

To improve the studio instruction methods and accomplish the pedagogical goals of the project, the project settings were integrated with guidelines of the problem-based learning process. A modified nine-step version of the formal seven-step structure that is usually associated with PBL [17] was used for this project processing. The two added steps include evaluation and representation activities. The main steps followed in the ergonomics-based design project processing were:

1. **Problem assignment and team formation**: Sixteen third-year architectural digital design students divided into four groups were involved in the PBL-based design project. In the first session of the project, the studio supervisor (the author) introduced and explained the design problem. The student teams were formed and they were required to meet frequently physically and virtually to discuss the design problem situations that were selected to be unfamiliar and not having easy or straightforward answers.

2. **Problem comprehension and interpretation:** The studio supervisor checked how each group understood and interpreted the problem and asked the students to identify its statement and rephrase it in their own expressions. The students were encouraged to start exploring the multiple issues related to the problem definition and interpretation.
3. **Exploration of problem-related knowledge gaps**: The participant teams were asked to use their own knowledge and experience when discussing the problem and treat it as if they were personally asked to solve it in real life practice settings. At this stage, a brainstorming session was held to reveal what each team knows about the problem subject matters and its possible interpretations.
4. **Problem-related research**: Upon the identification of what was known and more crucially what was not about the problem and its possible solutions, the teams were asked to research the unknown areas and propose potential problem interpretations and come up with alternative proposals that were likely to explain and solve the problem situation. Once basic alternatives had been proposed each team then negotiated an area of exploration for each member to independently carry out his/her portion of the research.
5. **Design tasks allocations:** As a result of the previous step, a specific assignment was designated for each member of the group. These included the explanation of ergonomics principles and their applicability on building design, the investigation of kinetics in internal and external structures, the implications of responsiveness in architectural solutions and their methods of interaction with users or environments, the analysis of contextual influences and forces, developing programmatic requirements, environmental and site analysis, and configuration of different scenarios for needs and settings of each building user. Each of the four team members was assigned simulation studies of a family member of the proposed four house inhabitants.
6. **Problem re-interpretation:** After the individual research and after a sufficient time has elapsed to allow the research to be completed, each team was asked to meet again to discuss members' individual contributions and findings about the problem in light of the information discovered by the group members. At this stage, students were asked to define their solution criteria and their design goals.
7. **Proposal of solution alternatives:** Depending on a list of objectives and design criteria that each group was asked to define, students were expected to come up with alternative solutions.
8. **Solution evaluation:** All teams were asked to evaluate the proposed solutions against the preset criteria and objectives and to select the best fit solution.

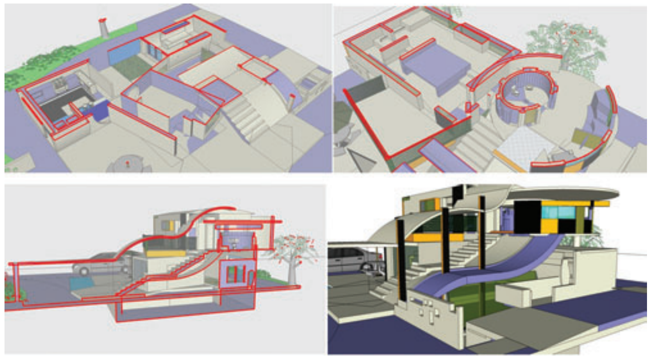
9. **Experiment presentation:** Finally, the teams were required to make a professional presentation of their problem interpretation, research, team management, proposals as well as their final solutions using different media. Each member of a group was responsible for the digital modelling of the animated experiences of a family member to examine how s/he uses every space in the house and how s/he moves between rooms horizontally and vertically. The representation should include an animated computer model, a physical model with transformable and movable parts, and animated details and supportive systems. In addition, for each stage in the process, design development steps were required to be documented in detail to clearly show the design derivation sequence as well as the impressions about this experiment. All group members helped in the animation of the four members' walkthroughs and the in-between steps; and the movable settings of structural elements and furniture pieces as responding adaptations to users' functional needs. Each group discussed their problem interpretations, solutions and new learning experiences. The students were also asked to evaluate their experiences and communicate their reflections and feedback about them to other students and jury members.

In summary of this approach, the first four steps of the collaborative part of the project processing focus on the team formation issues; the comprehension and interpretation of the problem, the realization of the gaps of knowledge and the potential areas of research; as well as on job allocation and assignment for team members. The fifth and sixth steps are related to data collection and analysis. The focus of the seventh step is on the proposal of solution alternatives. The eighth step is concerned with the evaluation of the findings and solutions. The concern of the ninth step is centred on communicating and presenting the experience to peers, supervisor and jury members.

This two-week collaborative part of the project was followed by two-week individual development of one of the alternative solutions, a combination of two or more solutions, or even the derivation of a new solution based on avoiding the problems diagnosed in the suggested alternatives. This part was tailored to emphasize the creativity and imagination of each student as customized to his/her pace, but after acquiring the experience and knowledge background from all team members.

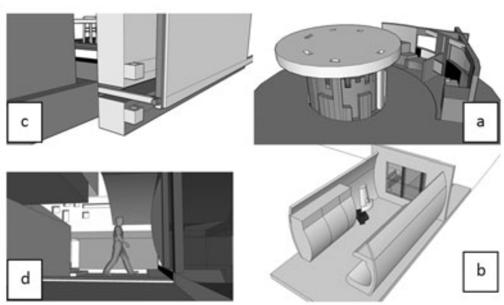
An example of the students' designs is illustrated in Figure 1. The figure shows various shots of the ergonomics-based generated house. Each room was designed to fit its user's needs and responds to his/her changing functions.

► Figure 1. Shots of the ergonomics-based adaptive house.

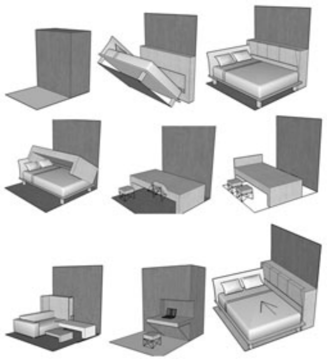


For example, the circular room and bath were designed to fit the wheelchair user physically disabled son. Everything in the room is designed to facilitate the wheelchair movements and to satisfy his painting hobby (Figure 2,a). Using similar ergonomics principles, the old grandmother's room was designed according to her physical abilities. It was located next to a semi-open courtyard that satisfies her gardening hobby but does not expose her to extreme outdoor climate conditions (Figure 2, b). In this room, the furniture pieces were designed to be easily accessible and operable. For example, closet doors were designed be opened from below and rotated around hinges that are placed on the upper axis of the closet to make clothes storage management as easy as possible for the old grandmother. Similarly, the room was designed with a large window that views the indoor garden. In this design solution, the difference in height between the tall husband and short wife, wheelchair user son and grandmother was solved by an operable floor slab that can be unfolded for short users and folded for tall ones (Figure 2, c). Similarly, the pleasant spatial experience of the tall architect owner of the house is illustrated in Figure 2,d.

► Figure 2. User-based ergonomic spaces.



Within the overall design of the ergonomics-based and functionally-adaptive house, students were asked to design multi-use flexible furniture pieces that can fit different situations. Using folding/unfolding, shrinking/expanding, sliding, and stacking operations, the same furniture pieces were supposed to function for sleeping, studying, dining, and sitting. An example of a multi-use furniture set is illustrated in Figure 3.



◀ Figure 3. Multi-use furniture set.

The design quality was evaluated based on the hard and soft presentations made by students, and on the process followed to develop the design. In addition, semi-structured interviews were held between students, supervisor and other academic staff members to clarify students' thoughts and experiences. Furthermore, a regular design jury was organized to evaluate the projects.

4. Results and discussion

In addition to jury members' feedback, semi-structured interviews and the author's (project supervisor's) observations, a short questionnaire was given to the participant students after the project presentation to report their feedback. All feedback measures produced some interesting findings. The major questions asked in the different evaluation methods were centred on three major subjects. These are the students' cognition of the new concepts and challenges of ergonomics and kinetics in design, their interaction and reaction to the new PBL learning method, and the effectiveness of computer aids and multimedia employment in understanding the problem and its visualization, representation and simulation of all the expected post-design scenarios associated with it and its possible solutions.

The main findings are related to the exploration and understanding of new concepts, the significance of the problem interpretations to its potential solutions, the emphasis on the different problem solving skills and on the integration of multiple areas of knowledge and on the power of applying different media, presentation techniques and multiple communication methods. They are also related to the higher level of enthusiasm when the focus is on students' active involvement in the learning process, the discovery of explicit design process guidelines, and the enhancement of team work management skills. The major findings are summarized in the following nine observations.

1. Since the project was conducted in the context of digital studio, students were required to put the computer aids to a maximum use.

They used the latest versions of multiple graphic, building modelling, visualization and animation software programs. Using these software packages, the animation programs, in particular, was essential to illustrate some concepts that were difficult to communicate using conventional manual media. All scenarios about motion-related transitions in the expected post occupancy life cycle of the house were represented using computer building simulation and animation packages. Other software also facilitated the working of different students on the same issue simultaneously using referencing and hyper-linking systems in software and integrative systems in hardware. Each team of students had considered a number of different options before choosing their final outputs. All predicted walkthroughs as experienced by each member of the proposed family were simulated to understand space utilization of each room and to test the spatial and visual flow as well as circulation patterns. Each student in the team was required to imagine her/himself in the position of a family member and simulate the expected needs and responsive functions of the house spaces and its furnishings from his/her eyelevel as well as according to his/her physical and psychological requirements. Examples of these are demonstrated in Figure 2, where the experience of the wheelchair user son, the tall architect, the short wife with home business, and the grandmother with limited physical capabilities, more sensitive psychological needs and gardening hobby. In this regard, the multi-media employment provided significant help to problem as well as solution visualization and communication.

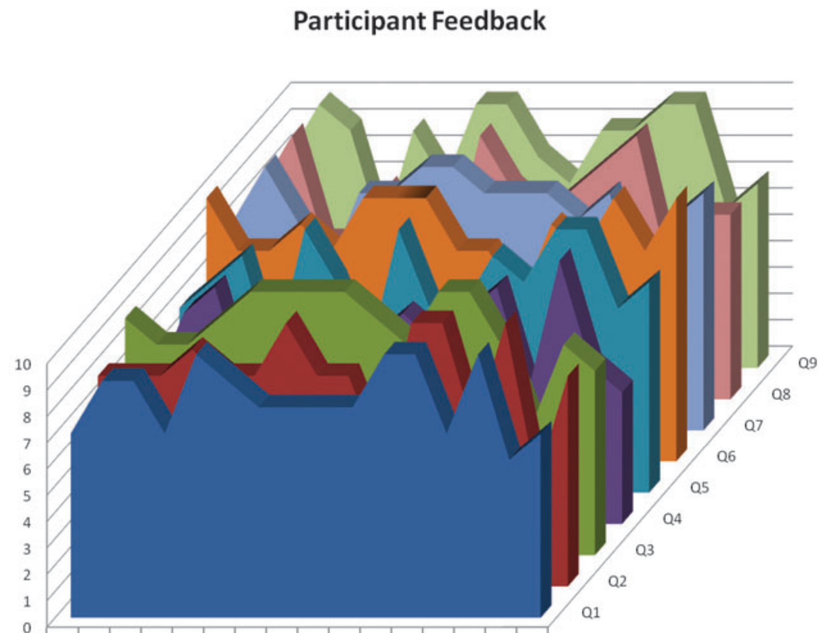
2. The use of online tools was very helpful in this project. Students were encouraged to use synchronous chat-tools throughout all the phases when physical meeting was difficult. Enhanced by the digital studio settings, this kind of computer-mediated communication allowed for direct interventions or reactions on both, students' and tutors' sides. In addition, asynchronous communication was facilitated by internet applications. It allowed the possibilities to reflect on the progress of a discussion, to work without any time pressure, to integrate recently acquired knowledge to exchange ideas, and to use a more structured way of discussion than in alive or synchronous discussions [18]. The computer applications supported this experience in many ways. They facilitated the understanding of the problem, the visualization of its solutions and motion-related aspects, the representation of the animated responsive metamorphosis aspects of architectural design, and the inter-group synchronous and asynchronous communication when physical collaboration was difficult to achieve. The computer aids used in this project may be developed into a future E-PBL project, where physical team management tasks can be replaced by cyber collaboration.

3. The finished product digital, physical and verbal representations demonstrated that each student group had understood the basics of ergonomics and their impacts on dynamic and flexible designing in four-dimensions. The students came up with different solutions based on different concepts of flexibility and mobility and different kinetic structural and supportive technical solutions.
4. The students' feedback indicated that the integration of the theoretical knowledge from different resources with design processing was improved.
5. The experiment showed that the problem interpretation is very important to its potential solutions. Students' reflections as communicated by their experience documentations and discussions revealed that they had to reinterpret the problem to their understanding and restructure it many times before they propose solutions or even research relevant data.
6. The studio tutor noted unusual high levels of concentration by student participants. The enthusiasm and excitement generated by this project was also high, with students proudly showing their animated movies to peers upon completion. The ambiguity and difficulty of the design problem posed a challenge that encouraged students to keep trying new solutions.
7. The designing process was different for each group. While some focused on the structural and constructional aspects as design generators, others highlighted the solutions offered by smart buildings or systems inspired by other bio-creatures.
8. The design methodology and process was cleared and could be stated more explicitly than in the traditional design studio methods. Through the documentation and later presentation of all pre-design and design steps, the students were able to formulate a designing strategy and design process guidelines that could help them to inform their future designs.
9. In the organizational phase of the PBL-process, a tutor supervision or intervention was necessary to help students define objectives, distribute responsibilities and allocate tasks within team members in order to guide and optimize their progress.

In addition to these observations, a structured questionnaire was conducted to enable participant anonymously evaluate reflections about specific aspects of the project implementation experiment. In this questionnaire, nine questions were asked to test how this project affects methods of concept formation and generation, efficiency of cross-disciplinary knowledge integration, ergonomics impact on architectural design, connection to real life problems, learning techniques, evaluative and critical thinking and digital communication skills. The questions and answer statistics

	Responses are based on a 10 point scale where 0 indicates no agreement and 10 indicates the strongest agreement with the statement: “This project helped me to”	Average Score	Standard Deviation	Total Score There were 16 respondents	Design Aspect
Q1	Understand new concepts that affect design	8.31	1.30	133	Concept generation
Q2	Link knowledge from different fields together	8.00	1.75	128	Knowledge integration
Q3	Focus on users’ experiences as generators of design	8.69	1.40	139	Ergonomics
Q4	Interact actively with architectural design	7.06	1.61	113	Participant involvement
Q5	Link course to real life practice	8.00	1.63	128	Problem reality
Q6	Explore new educational experience	8.75	1.18	140	Learning skills
Q7	Think deeply about design problems and limitations	8.50	1.37	136	Critical thinking
Q8	Develop my evaluation skills	7.50	1.67	120	Evaluative skills
Q9	Develop my presentation skills	8.38	1.59	134	Communication skills

▲ Table 1. Questionnaire contents and statistics



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Q1	7	9	9	7	10	9	8	8	8	8	10	10	7	10	6	7
Q2	8	8	8	9	8	8	10	8	8	5	10	10	6	10	4	8
Q3	9	8	8	9	10	10	10	10	9	8	10	10	8	5	8	7
Q4	5	8	9	5	7	8	6	7	8	7	8	9	5	10	6	5
Q5	7	8	9	5	10	8	5	10	7	7	9	8	10	10	7	8
Q6	10	8	8	9	8	10	10	10	8	8	6	9	8	10	8	10
Q7	8	10	8	6	9	9	10	10	9	9	9	8	9	5	8	9
Q8	8	10	6	6	8	6	5	10	8	7	8	9	10	5	7	7
Q9	8	10	9	5	9	7	10	10	8	7	9	9	10	10	6	7

▶ Figure 4. Questionnaire results for each student and question.

are illustrated in Table1.

The scores recorded for all questions are high. This indicates that all the goals of the project were achieved successfully. However, slight variations can be noted between question scores to point out that success in some aspects were higher than others. The highest score was given to the new PBL technique which seems to improve the educational experience (Q6). The second highest score was assigned to the project positive impact on the understanding of users' experiences and their associated ergonomics principles on the concept derivation of building design (Q3). The third grade was scored for fostering deep thinking about the design problem and its limitations and how these affect the functionality and form of the final generated product (Q7). The fourth score was given to improving communication and presentation skills using digital media (Q9). The least score was recorded for the question about how the project helped students interact actively with the architectural design problem (Q4). The standard deviations of all the scores are not high. Responses of participant students to the questionnaire are illustrated in Figure 4. The horizontal axis (X-axis) of the three-dimensional chart of Figure 4 represents the 16 student series, the (Y-axis) represents responses to the nine questions, and the perpendicular axis (Z-axis) represents the scores (on a 0-10 scale) recorded for each question by each student. Each continuous strip shows all students answers for each question. As Figure 4 shows, the results seem homogenous with relatively small variations. The most heterogeneous responses were assigned to Q2 which questions how the project helped the students to link knowledge from different fields together. This may be explained by the fact that this aspect is highly associated with personal backgrounds, desire and enthusiasm to retrieve and apply their accumulative knowledge repertoire.

The project achieved most of its preset goals in improving learning skills and incorporating new trans-disciplinary principles into architectural design. In this regard, findings from this project experiment support those from a previous knowledge networking implementation in architectural design as conducted by this author [19]. Similarly, the goal of digital employment of computer aids for the visualization and simulation of the "alive" settings of the house and expected behaviours of its end-user's seems to be successfully achieved.

The project still needs development to improve students' interaction with the design problem and to enhance their evaluative skills (as indicated by responses to Q4 and Q8 of the questionnaire).

5. Conclusions

The project discussed in this paper investigates the digital application of ergonomics in architectural design as a functional guidance and formal generator. It applies digital tools to model the impact of human anthropometrics of various end-users on space design, and to simulate time-based animated interactions between users and flexible structures.

To increase the effectiveness of this experiment, the introduction of ergonomics principles was coupled with problem-based learning (PBL) approach that is widely considered more suited to practice-oriented professional teaching. The time-based lifecycle-related project implementation in a digital studio of architectural design course was conducted using PBL techniques. The experiment seems to support the author's initial hypothesis that this combination of ergonomics, kinetics and PBL techniques introduces an effective approach for teaching systematic architectural design methodologies, strategies and techniques. Evidence from the project results shows that this student-centred learning approach not only maintains students' interest, but raises levels of enthusiasm and commitment significantly. There are real benefits for students in becoming active seekers of knowledge where they build their own design knowledge based on their own defined gaps and in their personalized comprehension pace. In this experiment, the whole design teaching experience changes from generalized archetypal frameworks into customized versions that fit individual students.

Feedback of the participants in the project implementation was measured by a structured questionnaire in addition to student documentations during the experiments about their reflections on the experiment, and tutor and jury members' observations. The feedback results indicate that the computer-supported hybrid methodology where trans-disciplinary extrapolation of ergonomics guidelines from other engineering applications into architectural design, and the PBL-based design approach can develop learning competences, emphasize users' impact on shaping their built environment, foster deep reasoning about design problems and their limitations, and develop visualization and presentation techniques. The experiment still needs enhancement to improve participants' evaluative skills and increase their active interactions with the design problem at hand. This may be achieved by building complementary physical models that can be more engaging and involving to designers during design development.

The user-oriented ergonomic approach coupled with the employment of digital tools proved to be effective in guiding an informed, systematic and structured design processing and in improving the quality of design functionality and forms. Furthermore, the project described in this paper indicates that the PBL approach can foster deep thinking, and to keep up a high level of enthusiasm to explore new concepts such as those of responsive architecture, dynamic structures and flexible furniture. It fits higher education where values such as independency, teamwork, initiation, and student active involvement are desired. It also fits design teaching that encourages self knowledge-building, self-evaluation and informed decision making.

As a result of this project implementation, it is suggested to consider ergonomics in the early phases of the design development processes. Human-centred design including space usability and ergonomics assessments seem essential to designs that are optimized functionally. Existing computer-aided design, visualization and simulation software appear to provide the necessary media for ergonomics analysis and their impacts on responsive artificial environments.

Future extensions of this research include the incorporation of digital human modelling (DHM) software into similar projects' settings and the augmentation of physical gaming simulation where participants play various roles of potential end-users to report their realistic reflections about human-building interactions.

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