ARLE GPS: A computational tool to aid solve the creative design of a house. Case study.

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Research Article

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Abstract

The computational tool ARLE GPS "geometric planning solver of floor plan layout", converts the spatial planning of a house, conceptualized as a "wicked" problem, into a "well-defined" problem; and thus, helps the architect to solve it in a rational, innovative, and creative way, using a physical-biological meta-model. The physical model simulates solutions of the candidate FPL repetitively, in real time, and evaluates the geometric qualification of the FPL, representative of the quality of the solution, in an analogy with the physical functional performance of the house. The biological model makes it possible to build and explore design spaces, with the goal of retrieving information about inheritance and genetic transmission of high-performance solutions, to transcribe them into the development of innovative and creative designs. Thus, ARLE GPS evaluates creative design against the social value of the house, represented by its utility/functionality, and the quantitative innovation established by the fulfillment of the home purpose, by the user. Through geometric qualification (*QQL*) and optimization, in relation to the defining qualification of the house's required performance. (*QQA*). Associated with the evaluation of the house's performance over its useful life, represented by its usability. Computed by the ARLE GPS robust design model, through the geometric cost of losses (*AN*) variable, induced by the FPL design solution, as in the case of confined rooms, which persist during the house's lifetime.

1. Introduction

The case study presents the application of the ARLE GPS tool acting as an assistant to the architecture student, in the habitational design process. Helping him to convert the "wicked" spatial planning problem of a floor plan layout (FPL) into a "well defined" problem (Buchanan 1992). Since, this is a critical issue of the process, especially for the student who is beginning his contact with the complex problem of design (Lawson 2005 p.31). Design is a social process of creating artifacts, which aims to conceive and make available new and better situations for humanity. (Gero 1990; Schaathun 2022). Designers play a vital role in this effort to make the planet a better world. However, one of the challenging factors in achieving this goal is the fact that most design problems are characterized as being "ill-defined" or "wicked" (Casakin and Wodehouse 2021). According to Sosa (Cascini et al. 2022), in an ill-defined problem, the requirements, constraints, and evaluation criteria, are unclear. This lack of clarity/explicitness of the problem particularly in the conceptual phase of design, induces a vastness of solution possibilities; the formulation of varied strategies to attack and overcome the problem, and that results in different implications and difficulties for solving the problem (Wortmann 2018), such as: meeting the multiplicity of objectives, requirements, constraints, viewpoints and tastes (Sönmez 2018); refining the solutions without compromising the problem objectives (Bao et al. 2013); finding the best solution to the problem (Weise et al. 2009); quantifying the quality of the solution (Dino 2016); objectively judging the solution (Archer et al. 2005). In case the problem is clear, such as getting a cup of coffee, its solution follows a rite of possibilities, strategies, and solutions previously available, and in the domain of the solving agent/individual. However, in the case where the problem is ill-defined, and, without a consensus on what a good solution is, it requires greater understanding, exploration, skill, effort, intuition, and creativity to

solve it, such as the case of an architectural design (Ball and Christensen 2019). In this case, the data initially available, are not sufficient and clear for students to solve the problem simply by transforming, reducing, optimizing, or overlaying the information provided (Archer 1979). And, therefore, they problems cannot be completely solved using routine problem-solving processes applying pre-established strategies and rules, either by manual or computational mode (Casakin and Wodehouse 2021). Due to the lack of an established and precise method for solving them (Medjdoub and Yannou 2000). Thus, the student is compelled to use his knowledge and experience and apply his ability/faculty of intuition and creativity to solve this type of problem (Doulgerakis 2007). Attributes and abilities that in most cases he does not have yet. Intuition plays a significant role in decision making, as it allows the designer to idealize relationships of elements and concepts, and make decisions instantaneously, following recognized patterns based on their experience and ability (Taura and Nagai 2017). Creativity in turn constitutes an important topic related to solving these design problems (Casakin and Wodehouse 2021). It has the potential to induce the designer in the systematic search to satisfactorily solve an intended function, satisfy specific performance criteria, generating and selecting creative design alternatives (Cross 1997; Clevenger and Haymaker 2011; Bradner et al. 2014). One of the issues concerning the topic of creativity focuses on the investigation of distinguishing creative design from the act of design. With the goal of establishing when and how a designer is being creative while he designs (Gero 2020). The act of design involves exploration, that is, defining which variables are appropriate for the solution of the problem, and formulating the strategy to be used for this purpose. The exploration process, on the other hand, involves finding the variables and attributes that allow setting the goals, as well as making and implementing the decisions (Gero 1990). Regarding the process of creativity, the first step is to extract and analyze the customer's needs (Fidler 2021). Once the design needs/brief are defined and frozen, creativity happens within the space of that briefing (Verganti et al. 2020). Creativity is conceptualized from various approaches: artistic expression, technological innovation, cognitive phenomena; as well as it is described considering various criteria to categorize a solution as creative (Davis and Gristwood 2016a; Cascini et al. 2022). One of the most employed is as a function of the degree to which the artifact is useful or novel, or both. Utility represents the social value of artifacts, which is established by their actual use, while novelty is defined, in terms of an artifact, by one that does not resemble another previously designed or known (Shah and Vargas-Hernandez 2003; Sarkar and Chakrabarti 2011). The activity of the designer's creativity is crucial to the design solution, and production of innovative artifacts. It represents the changes introduced in society by science and technology, from the perspective of design solution, according to the quantitative or qualitative innovation model. From the quantitative innovation perspective, the design is generated to fulfill a pre-assigned purpose or objective of an existing artifact. As in the case of the commissioned design of a house/apartment. Thus, the contracting/ requester provides the required specifications of the artifact based on their needs. In contrast, from the qualitative innovation perspective, the purpose (specifications) of a product become clear as its design process progresses. In this case, the products that are being designed do not exist, yet they carry with them the expectation of bringing new lifestyles to society (Taura and Nagai 2017). Now, it can be exemplified by the changes that will come to society, regarding design, manufacturing, and use of products, software's, services/activities, which will be introduced with the advent of the metaverse. Which aims to create a collective, shared virtual world

and replicate reality through digital devices, using "virtual reality", "augmented reality", and "internet" technologies. While there is a vast amount of literature related to creativity, there is a limited amount aimed at assisting architecture design students in the context of creative design developed in a studio (Casakin and Wodehouse 2021). To contribute to this issue and share a successful experience in the teaching learning process of architectural design in a design studio, particularly in relation to the process of generation and exploring the design solution, and its interface with the action-decision field of design resources, and with innovation and creativity, the case study is presented: ARLE GPS – A computational tool to aid solve the creative design of a house. The tool acts on the housing design process through an action-decision model, and the robust design, in solving open and significant questions for design research, particularly in relation to the evaluation of design quality. Which according to Goldschmidt and Matthews (2022), to be considered as a acting with good performance, it must solve mainly the following questions: resolve an important open question, which models the design process, in a robust way, and with effective metrics; present a new perspective for the solution of the question, through the generation of new hypotheses, and a new resolution procedure, shedding new light on design phenomena, and opening new lines of investigation; show what are the keys to successful decision making for resolving the open question; improve the practice of design problem solving; fill a gap in the existing literature, and expand the state of the art; meets the fundamental principles of ethical research through data transparency. These issues must be complemented, according to Boujut (Papalambros 2015), in relation to the domain of the process, through a methodological tool that allows to be shared, evaluated, discussed and with easily reproducible and verified results. Which are fully met in the case study presented and can be evaluated through the application of the ARLE GPS tool, and the results achieved.

2. Structuring The Arle Gps Computational Tool

The establishment of an analogy model marks the initial action of structuring the ARLE GPS computational tool. The model is defined by collecting, quantifying, and qualifying the geometric planning variables of the FPL (floor plan layout), in an analogy with the functional and usability performance of the house, here represented by a verticalized house, i.e., an apartment (Martins 1999). These variables shape the horizontal plane and quantify and qualify its spatiality and configuration, which represent the two main geometric conversions of the FPL solution (Hillier 1998). The capture, quantification and qualification of the configuration and spatiality of FPLs is achieved through the relationship between the vertical and horizontal planes. Defined by the quantification and qualification of the variables surface area (*AU*), perimeters: internal (*PU*) and external (*PE*). On the other hand, the internal perimeter variable, when allocated to confined rooms (*PR*), or circulation rooms (*PC*), is defined as a non-qualifier. The useful surface area (*AU*) has the function of providing the horizontal plane used for dimensional modeling of the rooms of the house (Medjdoub and Yannou 2000). It establishes the spaciousness of the house, which defines an indicative and overriding attribute of its performance. Its participation in the qualification of the FPL is computed by the spatiality index (*IA*). The internal perimeters act on the house's performance by establishing the function of a generating system for the house's vertical planes. These planes define the demarcation of the walls, which delineate the physical

boundaries of the rooms, and reveal their spatial configuration (Peponis et al. 1997; Medjdoub and Yannou 2000; Sönmez 2015). Their share in qualifying this performance, is computed by the configuration index (*IP*). However, internal perimeters are computed as non-contributors to house performance when they are allocated to confined and circulation rooms (Nagy et al. 2017). Confined rooms are defined by the lack of a direct connection to the outside environment. The confinement is related to the problem of not allowing users direct access to sunlight, as well as hindering the exchange of air and heat with the outside environment, and not least, making it impossible for users to access the landscapes of the outside world. Its participation in this qualification computation is established by the confinement index (*IR*). The circulation room, on the other hand, does not have the function of a living room, and in this case, it is used as a passage and connection pathway, which configures a locomotion room (Bahrehmand et al. 2017). Its participation in this qualification computation is established by the circulation index (*IC*). The external perimeter has the function of establishing the shielding of the house in relation to external protection, climatic safety, and providing thermal and hygrometric comfort. It also establishes an access, exchange, and communication portal, at a physical, luminous, calorific, atmospheric, and visual level with the external environment of the house. In addition to providing aesthetic beauty to the house (Medjdoub and Yannou 2000). Its participation in the FPL qualification is calculated by the externalization index (*IE*). The condominium and symmetry perimeters define the section of the house's boundary perimeter located inside the building. These perimeters are not the exclusive property of the house, and do not appropriate the functions performed by the external perimeter (Hillier 2007). The differentiation between them, is that the condominium perimeter (*PX*) is shared with the collective area of the building, and the symmetry perimeter (*PY*) is shared with another house and establishes axes of symmetry between them. Therefore, in the analogy model, they are conceptualized as non-contributors to the FPL qualification and are not computed in the LEQC (Evaluation of geometric quality and layout cost) meta-model (Martins et al., 2021) DOI 10.13140/RG.2.2.21101.51681). However, they are contributors to the cost of converting the FPL into the house artifact and are computed for this purpose. The geometric variables quantified and qualified in the house performance analogy model represent the totality of the variables used for geometric planning of the FPL, and structure the LEQC meta-model which is converted into the computational tool named ARLE GPS (geometric planning solver), through spreadsheet editor software (Excel). The geometric variables of the FPL assembly are computed by the LEQC meta-model with the same degree of importance, i.e., the same weight. The LEQC meta-model aims to facilitate the tasks of students in the preliminary phase of FPL design, which are characterized by vagueness and uncertainty in decision making. It makes the design problem explicit/clear and assists the students in making decisions (Capilla et al. 2011). Defines a conceptual model of scientific modeling within a social context (Ritchey 2014). It is a simple mathematical representation of a complex high-fidelity simulator and explorer, which establishes a relationship between the performance of the artifact through the geometric parameters of the FPL design, outlines the paths to solution optimization, (Meckesheimer 2001), and evaluates them. Thus, enabling ARLE GPS to function as an assistant in the design process, especially in relation to the attributes of utility and quantitative innovation. (Taura and Nagai 2017).

3. Arle Gps Heuristic Approach To Fpl Planning And Design

The ARLE GPS heuristic makes it possible to convert the FPL spatial planning problem, conceptualized as ill-defined, into an explicit problem, by allowing, establishing, and providing:

• facilities in meeting the demands and desires of users;

• clear problem requirements and constraints, already in the conceptual design phase;

• conceptual strategies for design assembly and modeling: top-down, bottom-up, and case study genetics;

• holistic response based on objective judgment;

• computer-friendly support, focused and centered on the decision maker, not the design;

• reveal the cost of design decisions.

Through systemization:

• prioritize geometry over topology;

• remove uncertainties in decision making;

• simulate and evaluate the geometric solution of the FPL;

• progressively refine the solution space exploration result;

• explore the state of the FPL geometric solution in real time;

• crossing the feasibility space with the acceptability domain, producing a performance space within which one or more optimal solutions can be found;

• quantify the quality of the FPL design solution that meets the required performance;

• determine the geometric and monetary cost, through the geometric variables of the FPL;

• calculate the losses in the use of the apartment, depending on the magnitude of the qualifying variables of the FPL, applying the robust design approach;

• encode, index, retrieve and adapt cases;

- build design spaces;
- configure and limit the FPL project's solution space and build a measure of its performance;
- explore the design space using original and accurate search tool through the FPL's genetic code;
- measure the similarity or relevance of problems and cases;
- use existing designs as a reference to guide solutions for similar architectural situations;

- indicate the space susceptible to improving the quality of FPL solution, since there is no single best solution to a design problem in architecture;
- scientify the spatial planning of the FPL, counterpointing the use of drawing methods;
- function as a tool that supports creative ideas.

The ARLE GPS tool introduces a biological view into the architectural design process, through the construction of a biological model, structured by encoding the FPL's digital signature (Shi and Gero 2000), as shown in table 04. The genetic code of the FPL design informs the formation, functionality, zoning, order of assembly of the rooms in the house, connection between the rooms, and quantifies the geometric variables used in the assembly of the design of the house. It uses for this purpose the genes Gform, Gfunction, Gtopology, and Gspace. The dimensional unit of geometric variables is centimeters (integer number). The AR(Archer) LE(LECQ) GPS(Simon) tool works according to the conceptualization shown above and demonstrated in the case study below. Structured to assist students in creative design solutions. Its mathematical structure is defined by the LEQC metamodel and is derived from the systematic model proposed by Archer (1968), coupled with the GPS "(General Problem Solver)" problem solving principle proposed by Simon (1973, 1996) for solving ill structured design problems. Archer intended that his model coupled with the use and aid of the computer would constitute a tool that would free the designer from the burdensome concerns of the quantitative and repetitive tasks of the design process, so that he could use more time and energy in managing the qualitative and creative issues of the design solution. At the International Conference on Computers in Architecture in 1972, Archer exposed that this tool was not being used at the time yet would be in the future. He was particularly optimistic about the emerging area of computer aided architectural design (CAAD) (Archer 1972). However, these first-generation design methods, developed in the 1960s, were judged to be too rigid and mechanistic. A situation that has generated controversy and prevented its use in practice. Renowned and influential architects, engineers, and designers of the time, such as Christopher Jones, Christopher Alexander, and John Chris Jones became staunch opponents to this considered mechanistic principle, going as far as Alexander's comment 'people who are playing with computers have obviously become interested in some kind of toy' (Margolin 2010; Davis and Gristwood 2016ª). This toy has evolved in such a way that today it is an integral and indispensable part not only in the lives of design professionals, but in the daily life of all humanity. The CAAD era has consolidated, and now the artificial intelligence (AI) era is consolidating, with vast possibilities and opportunities, to facilitate the lives of architects in the conception of creative designs, via automatic data collection and construction of big data systems; interactive designer-computer systems; AI assistance in the conceptual phase of design (co-creative AI); automation of the design process (Cascini et al. 2022). Regarding the ARLE GPS tool, its usage occurs essentially in assisting architecture design students. However, the tool can also assist professionals in the field of architecture, as well as contribute in the CAAD and (AI) area. Due to the tool's ability to support several types of activities inherent to the process of automated generation of architectural designs, such as: exploration of the design space, simulation, optimization, evaluation, establishment of the breakpoint of the automated generation process, classification, and selection of optimized solutions. With emphasis on

the issues of the breakpoint, and quantitative evaluation, because the tools currently available do not support this type of activity.

4. Design Studio

The design studio in the present case, covers the study sessions held in a classroom that provides logistical support to students, in the process of teaching-learning architectural design (Goldschmidt 2002). Applied in the assistance to fifth year students of the discipline “project” of the Civil Engineering course of the State University of Maringá. The discipline lasts one semester, with two weekly sessions. It is important to consider and mention that the exercise of the civil engineer profession allows them to act in the architectural design (Passos 2004). This prerogative of the professional activity of civil engineers, implies that the teaching of the process of architectural design in the Civil Engineering course, with respect to the curricular grid of the course, is composed of a minimum of disciplines in architectonic design. This context portrays as a challenge to be overcome the issue of equipping students with a sufficient level of knowledge, reflective practice, skills, and competencies that enable future engineers to solve problems related to the planning and design of housing FPLs, in their professional life. They are then, equipped with the ARLE GPS tool and supplied with a representative database of a design space (family seven, shown in Tables 01,02,03), and its value space. The studio represents an ideal environment for training of the students, as it serves among its purposes to replicate a place that aims to portray, an environment of imitation of the real 'life' of future professionals, and to institute a learning process where students conduct design tasks, under the guidance of the instructor teacher (Adiyanto 2017). In this space, individually, they exercise design assignments, which are planned and executed to solve real-life problems (Goldschmidt 2002). Problem-based learning (PBL- problem-based learning) constitutes a good methodology to break the vicious cycle of the general principles of traditional teaching and experience an innovative and instructive education (Cabodevilla-Artieda et al. 2018). It is up to the teacher, in this case, to provide students with a real-world problem that is relevant to the lives of future professionals, as well as to determine how the project will be evaluated, and, to define the formula for assigning a grade for the work done (Bridges 2007). On the other hand, this studio followed a current paradigm of unconventional design studios, namely that of a digital studio. It is characterized by the replacement of traditional design representations (freehand sketches), by a digital medium, by the incorporation of computational equipment and the digital tools Auto CAD and ARLE GPS (Ismail et al. 2012; Hettithanthri and Hansen 2021), in this studio. Computer simulation using ARLE GPS software, for its part, is defined as a process involving the use of the computer to structure and simulate the geometric planning of the FPL of an apartment. Computational processing has the potential to relieve students from repetitive, tedious, and error-prone tasks (Frankel and Racine 2010). It can perform enormous amounts of repetitive routines without fatigue or error (Rodrigues et al. 2013). Assists students to run simulations repetitively, in real time, and evaluate the geometric qualification of the FPL in an analogy to the performance of the house artifact; and refine the result of exploring the solution space progressively until they obtain the desired optimization (Machairas et al. 2014). Regarding the design studio, the main academic feature of the study sessions, is the individual “one-on-one” crits, in which student and teacher discuss the work in

progress on a regular basis (Goldschmidt et al. 2010) throughout the study period (Dorta et al. 2016). The discussion about the task is coordinated by the instructor, during which questions are asked and answered, examples given, principles and precedents evoked, alternatives suggested, problem areas pointed out. The design sessions are apt for observation and documentation of the activities performed. However, in the present case the sessions were not documented. The students' final work is usually evaluated through a series of discussions and presentations. Through the results of the work performed, and presentation of the work, often publicly in an evaluation session, by a jury composed of invited professionals. (Dorta et al. 2016). Regarding the evaluation in this case, is processed mathematically, as a function of the degree of meeting the *QQL* qualification presented in the work, as discussed in section 10. In the present case, the students used for the solution of the problem the top-down assembly approach, and the genetic strategy of the case study.

5. Student Assembly And Design Of The Fpl

5.1 Top-down approach

The assembly of the FPL using the top-down approach is exemplified by the design of FPL 006 planned by student 06 (figure 01). Demarcated by structuring a geometric prototype of the FPL, using the ARLE GPS tool, to solve the following problem:

- FPL design of an apartment with required floor area *AU*=120.00±5.00 m²;
- functional configuration: three bedrooms (B,B1,B2);
- formation of two apartments per floor (*Nf*=2);
- functional program under the student's responsibility, through the components of the FPL structure, made available by the rooms: E1ULDOHT CFB1W1B2W2BP WKMGSB4W4E2 (table 01);
- FPL design requirement of a high-performance apartment (family 7 of design space): target area *AA* = 125.00m² and target performance *QQA* ≥19.50;
- building implementation on an existing physical site (provided: location, dimension, geographical positioning);
- obligation to comply with constructive public legislation.

Resources provided:

- ARLE GPS computer tool and auto CAD;
- systematic model of exploration and coevolution (figure 03);
- FPL database (design space - table 02);

- values space of design space (table 03);
- room dimensional values space (table 01);
- constructive public legislation that must be complied with.

Evaluation of the work

- requirement of meeting the minimum required performance $QQL \geq QQA$;
- evaluation according to the performance established QQL;
- assignment of the grade of the work directly proportional to the performance QQL.

Family seven defines the design space and value space of FPLs in the high-performance region. The required performance required for the apartment, in the proposed problem, is established using the equation AU=0.0164(QQL)³ (envelope) (figure 02), considering the target area AA=AU=125.0 m², which results QQL = 19.64 (computed), and QQA = 19.50 (adopted).

Table 01 - FPLs room size value space - Family 7 design space

Room	Area Min	Area Max	Area Average	Perimeter Min	Perimeter Max	Perimeter Average	Form favtor FF Area min	Form favtor FF Area max	Form favtor FF Area x perimeter avarage	Relation width (w)x length (L) Area min	Relation width (w)x length (L) Area max	Relation width (w)x length (L) Area x perimeter average
E1	2,03	4,23	3,02	5,70	8,50	7,34	4,42	3,92	4,22	1:2,45		1:1,95
U	21,42	45,87	29,75	18,15	29,07	24,71	3,92	4,29	4,53		1:2,15	1:2,80
L	14,10	26,35	19,06	15,45	23,98	18,78	4,11	4,67	4,30	1:1,60	1:3,15	1:2,15
D	11,30	24,26	17,46	13,55	20,70	17,20	4,03	4,20	4,12	1:1,30	1:1,85	1:1,60
H	7,28	12,76	10,31	10,80	14,3	13,02	4,00	4,00	4,05	1:1,00	1:1,00	1:1,35
T	1,48	2,94	2,00	5,12	8,57	6,06	4,02	4,08	4,29	1:1,25	1:1,45	1:2,10
C	1,00	8,91	4,30	4,00	20,00	10,54	4,00	6,70	5,08	1:1,00	1:9,00	1:4,25
F	7,44	10,77	8,95	11,00	13,20	11,98	4,03	4,02	4,00	1:1,30	1:1,20	1:1,00
B1	8,03	12,91	9,77	11,36	14,8	12,79	4,16	4,09	4,09	1:1,75	1:1,55	1:1,55
W1	3,25	10,1	4,27	7,52	13,03	9,00	4,22	3,97	4,36	1:1,90		1:2,35
B2	9,12	15,20	11,53	12,10	17,4	13,93	4,07	4,08	4,10	1:145	1:1,45	1:1,55
W2	4,16	4,16	4,16	8,18	8,18	8,18	4,01	4,01	4,01	1:1,15	1:1,15	1:1,15
B	10,48	18,42	14,43	12,53	19,35	16,73	3,87	4,12	4,40		1:1,60	1:2,40
P	3,20	9,45	5,39	7,20	12,00	9,13	4,02	3,90	3,93	1:1,25		
W	3,84	7,36	5,43	8,40	13,90	10,29	4,29	4,58	4,42	1:2,10	1:2,60	1:2,50
K	7,55	15,35	11,32	11,30	17,50	14,06	4,15	4,47	4,18	1:1,75	1: 1,30	1:1,80
M	7,05	9,55	8,30	10,80	13,30	12,05	4,07	4,30	4,18	1:1,45	1: 2,15	1:1,80
G	3,80	11,90	6,59	7,80	16,40	10,92	4,00	4,75	4,25	1:1,00	1:3,35	1:2,05
S	2,24	4,51	3,28	6,00	9,00	7,33	4,14	4,01	4,05	1:1,70	1:1,15	1:1,35
B4	3,00	5,60	4,14	7,00	9,60	8,18	4,04	4,06	4,02	1:1,35	1:1,40	1:1,20
W4	1,54	3,03	2,10	5,00	8,00	6,12	4,03	4,48	4,22	1:1,30	1:2,65	1:1,95
E2	0,88	2,60	1,61	2,30	6,60	3,64	4,00	4,09		1:1,00	1:1,55	

Table 02 - Database / Design Space family seven

Classificar Visualizar ...

Documentos > FPL family 7 >

Nome

54986 2 2 12 516 18 U CFB1W1B2BW KGSW4 1010200 1179900 0013710 0004035 0001105 0000455 0000725 0000000
56002 2 2 12 456 19 UT CB1W1B2BW KGB4W4 1017000 1162100 0014075 0003987 0000632 0000290 0000710 0000523
56094 2 2 13 470 22 UT CFB1W1B2BW KGSW4 1018100 1201100 0014230 0004023 0001124 0000000 0000400 0001274
56659 2 2 12 438 11 E1U CB1W1B2BW KGSW4 1021000 1170600 0014616 0003781 0000955 0000000 0000690 0000000
57166 2 2 12 494 27 UH CB1W1B2BW KGSB4 1049000 1197800 0014098 0004180 0001226 0000000 0000000 0000640
57219 2 2 11 543 14 U CB1W1B2BW KGB4W4 1035100 1179700 0013490 0003860 0000680 0000375 0001000 0000000
57296 2 2 13 484 21 E1UH CB1W1B2BW KGSW4 1046800 1193700 0014768 0004376 0000903 0000000 0000000 0000542
57825 2 2 13 535 19 U CFB1W1B2BPW KGB4W4 1084800 1240200 0014507 0004090 0001336 0000525 0000960 0000000
57924 2 2 15 520 12 E1LDHT CB1W1B2BW KGB4W4 1065800 1222200 0014825 0004705 0001035 0000000 0000710 0001300
58101 2 2 12 526 19 UH CB1W1B2BW KGB4W4 1080100 1240200 0014207 0004090 0001236 0000525 0000980 0000000
58118 2 2 14 483 22 UHT CB1W1B2BPW KGSW4 109 Data da criação: 19/12/2021 19:07 0979 0000000 0000960 0001195
58560 2 2 12 498 12 UH CB1W1B2BW KGSW4 11021 Pasta vazia 23 0000329 0000690 0000000
59121 2 2 12 509 14 UH CB1W1B2BW KGSW4 1116800 1298900 0015074 0003845 0001140 0000805 0001040 0000000
59176 2 2 12 460 29 U CFB1W1B2BW KGB4W4 1105400 1218800 0014940 0003267 0001419 0000382 0000890 0000000
59378 2 2 12 489 15 UT CB1W1B2BW KGB4W4 1079500 1231000 0014205 0004285 0001140 0000000 0000850 0001171
59645 2 2 12 427 09 U CB1W1B2BPW KGB4W4 1076000 1239900 0014834 0003947 0000806 0000000 0001408 0000800
59692 2 2 12 511 14 E1U CFB1W1B2BW KGW4 1087000 1297900 0014288 0003840 0001155 0000820 0001050 0000000
59769 2 2 13 501 17 U CFB1W1B2BPW KGSW4 1139800 1300500 0015133 0004149 0000890 0000665 0001085 0000000
60198 2 2 14 564 18 E1LDT CB1W1B2BW KGB4W4 1124500 1298100 0016050 0004650 0001535 0000230 0000860 0001170
61052 4 2 11 414 08 U CB1W1B2BW KGB4W4 1108700 1250800 0013840 0002585 0001300 0000750 0000870 0003940
62474 2 2 15 558 28 E1LDT CB1W1B2BW KGSB4W4 1189500 1366800 0015880 0004969 0001135 0000409 0000740 0001365
62662 2 2 12 492 14 UH CB1W1B2BW KGB4W4 1188700 1352800 0014600 0004255 0000785 0000675 0000990 0000000
62758 2 2 12 436 18 U CB1W1B2W2BW KGB4W4 1153500 1331900 0014565 0003697 0000631 0000700 0000780 0000823
62997 2 2 11 437 09 U CB1W1B2BW KGB4W4 1195200 1349200 0015113 0003670 0000570 0000835 0001260 0001460
63835 2 2 13 522 26 U CFB1W1B2BPW KGB4W4E2 1210800 1385800 0016220 0004480 0001330 0000330 0001690 0000640
65126 2 2 14 532 18 UT CFB1W1B2BW KMGB4W4 1270600 1461700 0016700 0004195 0001680 0000550 0001490 0000560
65743 2 2 12 470 12 LD CB1W1B2BW KGB4W4 1195000 1352600 0014722 0004150 0000680 0000625 0001040 0000560
67457 2 2 12 469 12 UH CB1W1B2BW KGB4W4 1260100 1428700 0015705 0003940 0001145 0000510 0001090 0001580
72950 2 2 14 503 16 UHT CB1W1B2BW KMGB4W4 1491100 1678100 0018320 0004775 0001370 0000360 0001160 0000700

Table 03 - FPLs qualification value space - Family 7 design space

Geometric Index	Abreviate	Minimum	Maximum	Average	Standard deviation
Form	*FF*	4,27	5,63	4,88	0,37
Vertice	*V*	8	29	16,5	5,91
Configuration	*IP*	6,0	7,59	7,02	0,32
Externalization	*IE*	1,48	2,13	1,81	0,16
Circulation	*IC*	0,30	0,88	0,56	0,17
Confinement	*IR*	0	0,77	0,29	0,28
Qualification	*QQL*	18,02	20,44	18,64	0,53
Qualification 125	*QQL125*	18,45	19,72	19,27	0,35
Cost/m² (dólar U$)	*VGL*	368,83	467,60	428,39	21,20
Cost qualification (U$)	*VQL*	2391,04	2945,75	2603,63	149,97
Cost qualification	*VAQ*	54986	74176	60805	4626

The process begins with the student defining the program/briefing for the apartment. Exemplified by the program proposed by student 006, which is composed of the UOHT CB1W1B2W2BW KGB4W4 rooms, and defines the Gfunction gene. Initially she proceeded to assemble the geometric prototype using the minimum values of the surface areas of the rooms of the FPLs - Family 7 design space dimension values, (Table 01), which resulted in the value of *AU* = 93.23m², below the required value (120±5 m²) In this case, a second prototype is assembled, using the average values of the areas of the rooms, which resulted in the value of the *AU* area = 130.41 m², above the required value. Finally, the simulation is performed using the average areas for the CB1B2BW B4W4 UHT rooms, and the minimum areas for the O W1W2 KG rooms, resulting in a value of *AU* = 118.83 m², thus meeting the required value. Being considered for the assembly of this prototype, the condition of no confinement of the living rooms, for the positioning of the solution in the high-performance region of the value space. Once is defined the areas of the rooms; the respective perimeters are established as a function of the value space of the dimension of the FPL rooms (Table 01). Once the area and perimeter of the rooms are known, and their corresponding form factors (*FF*), the length: width relations are extracted, which make it possible to determine the dimensions of the rooms considering the shape of rectangular polygons (orthogonal geometry), through the equation makes it possible to establish the width (*W*) and the length (*L*) of the room. In this step of the simulation process, ARLE GPS computes the spaciousness, internal configuration, and circulation and confinement indexes. Missing to compose the geometric prototype, the form factor, number of vertices of the FPL polygon, and the exteriorization index. Are obtained the form factor *FF*, and the number of vertices *LV* using the statistical techniques of regression, established by response surface (RSM), according to the polynomials shown in figures 09 and 10. The computed values for these variables are equal to *FF* = 4.90, and *LV* = 19. These values allow the student to have a description of the format of the FPL polygon, and its respective numbers of sides, as well as making it possible to search for FPLs with similar *FF* in the design space of family seven. Portrayed by the FPLs 143, *FF*=4.94; 152, *FF*=4.89; 171, *FF*=4.92; as shown in Figure 04. Knowing the form factor *FF*, and the area of the FPL, and considering in this case the prototype as a sketch without walls, with *AT*=*AU*, the value of the boundary

perimeter of the FPL polygon is obtained through the equation $FF = PF/\sqrt{AT}$ (perimeter of the polygon, PF=53.41m).

To structure the prototype, the size of the external perimeter, the condominium, and the symmetry are not yet computed. For this purpose, is defined the exteriorization index using the data of the family seven, which can also be established by response surface. Since the FPLs of family seven are in the high-performance region of the design space, the values of the average indices of the FPL qualification indices, compose a space of solutions that meet the required performance required for the problem. And in this case, is adopted $IE = 1.81$. Computing the size of the external perimeter through the equation $IE = PE/2\sqrt{AT}$, and obtaining the value of 39.45 m. Thus, making it possible to complete the structure of the geometric prototype of the FPL with the value of the sum of the condominium perimeter and symmetry $PX + PY = 53.41 - 39.45 = 13.96$m (Martins et al. 2021). The student then completes the ARLE GPS prototype, with the input data provided (*Nf*, *AA*, *QQA*), with the type of finishes adopted for the floor/ceiling and walls of the rooms, and their cost, and ARLE GPS provides for the design modeling, the following information:

- FPL formation: two apartments per floor;
- connections to the external environment: two;
- number of functional environments: fifteen rooms;
- form factor (*FF*) of FPL: equal to 490 (*FF* multiplied by one hundred = integer);
- number of sides of the FPL polygon (equal number of vertices *LV*): nineteen;
- functionality of the apartment: social zone UOHT; intimate zone CB1W1B2W2BW; service zone KGB4W4;
- order of assembly of the FPL structure and connections between the rooms:

{[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]};

according to the model:

Assembly parts - E1ULDOHTCFB1W1B2W2BPWKMGSB4W4E2

{ - start assembling the artifact

} -end assembling the artifact;

[-start the assembly of a block of the artifact;

]-end the assembly of a block of the artifact;

→ -process the connection;

(- process the multiple connections;

) - finish multiple connections;

ϵ - connect the next part with the "U" part of the artifact assembly;

- dimensions of the rooms (rectangular polygons): width and length.

And provides as evaluation values of the candidate case (geometric prototype) (table 04):

- floor area *AU* = 118.83m², meets the required floor area = 120±5m²;
- geometric qualification *QQL* = 19,90 >*QQA*;
- monetary cost of the FPL solution, *VGL* = 422.79 U$/m²;
- nominal area *AN*= 133.87m² > *AU* (geometric gain, according to the LEQC approach of robust design);
- monetary cost of geometric qualification *VQL* = 2524.92 U$/*QQL*;
- geometric cost of geometric qualification *VAQ* = 59719 cm²/*QQL*, (5.97 m²/*QQL*);

FPL genetic code:

- formation gene (Gform): 2 2 15 490 19;
- function gene (Gfunction): UOHT CB1W1B2W2BW KGB4W4;
- topology gene (Gtopology): {[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]};
- space gene (Gspace): 1188300 1188300 0016730 0003945 0001396 0000000 0001060 0000000.

Table 04. Geometric planning/prototype of FPL 006

006	Identification																								
Layout	Sector	code	Room Functional spaces	Width Wi (m)	Length Lg (m)	Area Au (m^2)	Perimeter Pu (m)	Empty perimeter Pp (m)	Circulation perimeter Pc (m)	Confined perimeter Pr (m)	Floor		Perimeter												
											Dry (Ad)	Wet (Aw)	Dry (Pd)	Wet (Pw)											
Functions and Dimentions	Social Zone	E1	entrance 1																						
		U	living & dining	3,26	9,13	29,75	24,71				x		x												
		L	living																						
		D	dining																						
		O	home office	2,70	2,70	7,28	10,80				x		x												
	41,5 %	H	home theater	2,77	3,73	10,33	13,00				x		x												
		T	toilet	0,98	2,05	2,01	6,06					x		x											
	Intimate zone	C	circulation	1,00	4,30	4,30	10,60		x		x		x												
		F	family room																						
		B1	bedroom 1	2,51	3,89	9,76	12,79				x		x												
		W1	bath 1	1,34	2,42	3,24	7,52					x		x											
		B2	bedroom 2	2,72	4,23	11,51	13,93				x		x												
		W2	bath 2	1,34	2,42	3,24	7,52					x		x											
		B	master bedroom	2,42	5,94	14,43	16,73				x		x												
	43,7 %	P	closet																						
		W	master bath	1,49	3,64	5,42	10,26					x		x											
	Service zone	K	kitchen	2,17	3,47	7,53	11,30					x		x											
		M	meal room																						
		G	laundry	1,95	1,95	3,80	7,80					x		x											
		S	store room																						
		B4	bedroom 4	1,85	2,23	4,13	8,16				x		x												
	14,8 %	W4	bath 4	1,04	2,02	2,10	6,12					x		x											
		E2	entrance 2																						
	Total					118,83	167,30	0,00	10,60	0,00	91,49	27,34	110,72	56,58											

2	Apartments / floor (Nf)	Entries (Ne)	2
Geometric variables	Variable	Unit	Abbreviate	Value
	Total Area	m²	AT	118,83
	External perimeter	m	PE	39,45
	Condominium perimeter	m	PX+PY	13,96
	Symmetry perimeter	m		
	Layout figure vertices	u	LV	19
Cost (euros)	Variable	Unit	Abbreviate	Value
	Dry floor	(U$) / m²	VAd	127,31
	Wet floor	(U$) / m²	VAw	125,08
	External perimeter	(U$) / m	VPE	328,80
	Dry internal perimeter	(U$) / m	VPd	105,60
	Wet internal perimeter	(U$) / m	VPw	159,70
	Cost of the layout solution			
	Cost/m²	(U$) / m²	VGL	422,79
	Total cost	TVL (U$)	50240,47	
Target layout	Variable	Unit	Abbreviate	Value
	Useful Area	m²	AA	125,00
	Geometric qualification	value	QQA	19,50

Layout Indexes	Abbreviate	Value
Form Factor	FF	4,90
Externalization	IE	1,81
Spaciousness	IA	10,90
Internal Configuration	IP	7,67
Circulation	IC	0,49
Confinement	IR	0,00

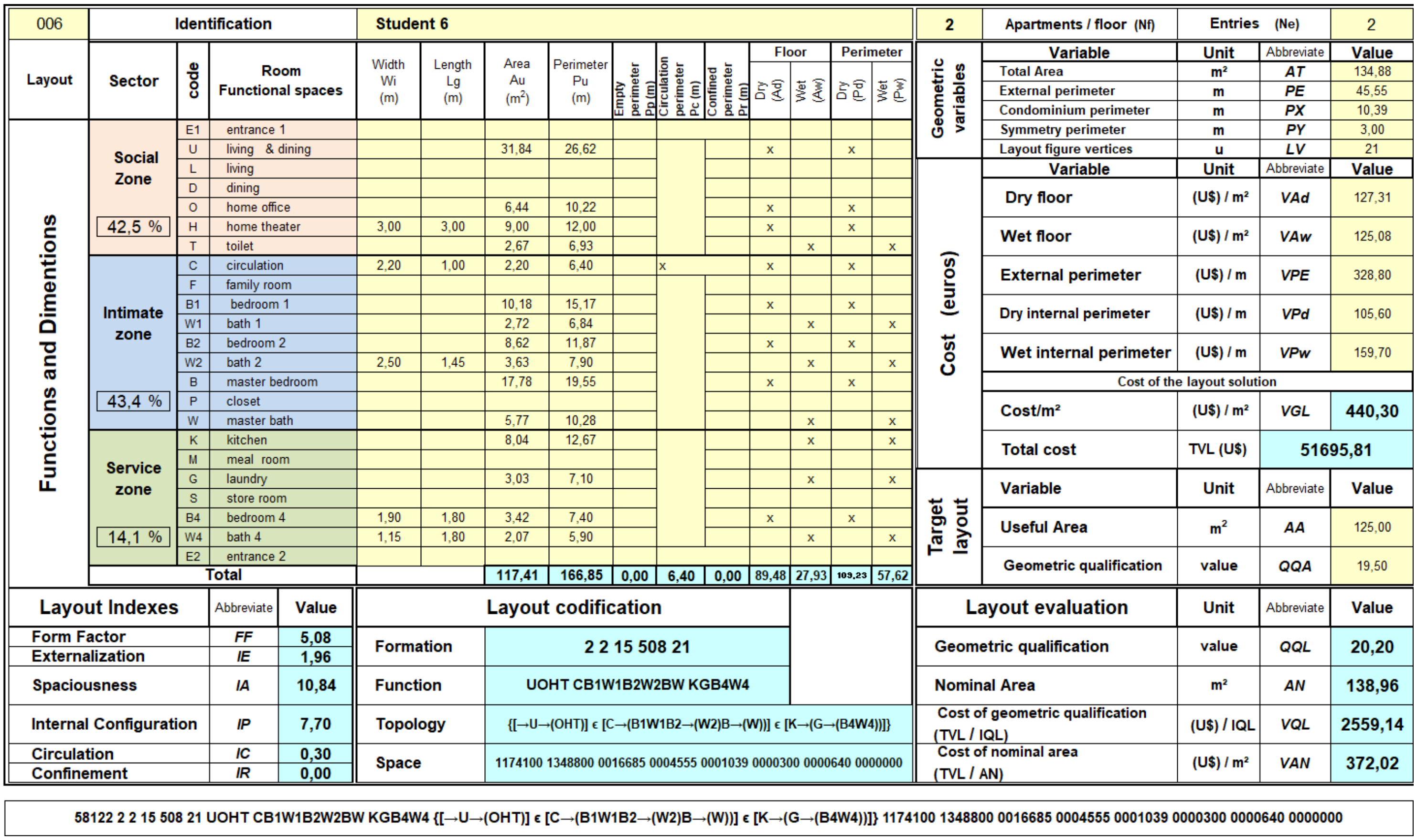
Layout codification	
Formation	2 2 15 490 19
Function	UOHT CB1W1B2W2BW KGB4W4
Topology	{[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]}
Space	1188300 1188300 0016730 0003945 0001396 0000000 0001060 0000000

Layout evaluation	Unit	Abbreviate	Value
Geometric qualification	value	QQL	19,90
Nominal Area	m²	AN	132,81
Cost of geometric qualification (TVL / IQL)	(U$) / IQL	VQL	2524,92
Cost of nominal area (TVL / AN)	(U$) / m²	VAN	378,29

59719 2 2 15 490 19 UOHT CB1W1B2W2BW KGB4W4 {[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]} 1188300 1188300 0016730 0003945 0001396 0000000 0001060 0000000

Students model and convert the geometric prototype into an FPL design directly by a digital means using the Auto CAD tool. Their task is to position the parts (assembly) in the FPL structure and model them (topology) until it can capture the FPL design that meets the requirements, constraints, and demands of the problem, as shown in Figure 01 and table 05. The students are supported in this task by the systematic exploration and coevolution model, which promotes the continuous simulation and evaluation process (loop) between planning and topology modeling (Maher et al., 1996; Yu et al., 2015), shown in figure 03. A relevant requirement and the consequent restriction applied in the modeling and generation of the FPL design, particularly in relation to the dimensions and the resulting shape of the FPL polygon, is established by the compatibility of the dimension of the terrain, the implementation of the building on the terrain, with the requirement to meet the constructive public law.

Table 05 - ARLE GPS - FPL 006



006	Identification	Student 6												
Layout	Sector	code	Room Functional spaces	Width Wi (m)	Length Lg (m)	Area Au (m²)	Perimeter Pu (m)	Empty perimeter Pp (m)	Circulation perimeter Pc (m)	Confined perimeter Pr (m)	Floor Dry (Ad)	Floor Wet (Aw)	Perimeter Dry (Pd)	Perimeter Wet (Pw)
Functions and Dimentions	Social Zone 42,5 %	E1	entrance 1											
		U	living & dining			31,84	26,62				x		x	
		L	living											
		D	dining											
		O	home office			6,44	10,22				x		x	
		H	home theater	3,00	3,00	9,00	12,00				x		x	
		T	toilet			2,67	6,93					x		x
	Intimate zone 43,4 %	C	circulation	2,20	1,00	2,20	6,40		x		x		x	
		F	family room											
		B1	bedroom 1			10,18	15,17				x		x	
		W1	bath 1			2,72	6,84					x		x
		B2	bedroom 2			8,62	11,87				x		x	
		W2	bath 2	2,50	1,45	3,63	7,90					x		x
		B	master bedroom			17,78	19,55				x		x	
		P	closet											
		W	master bath			5,77	10,28					x		x
	Service zone 14,1 %	K	kitchen			8,04	12,67					x		x
		M	meal room											
		G	laundry			3,03	7,10					x		x
		S	store room											
		B4	bedroom 4	1,90	1,80	3,42	7,40				x		x	
		W4	bath 4	1,15	1,80	2,07	5,90					x		x
		E2	entrance 2											
	Total					117,41	166,85	0,00	6,40	0,00	89,48	27,93	109,23	57,62

2	Apartments / floor (Nf)	Entries (Ne)		2
Geometric variables	Variable	Unit	Abbreviate	Value
	Total Area	m²	AT	134,88
	External perimeter	m	PE	45,55
	Condominium perimeter	m	PX	10,39
	Symmetry perimeter	m	PY	3,00
	Layout figure vertices	u	LV	21
Cost (euros)	Variable	Unit	Abbreviate	Value
	Dry floor	(U$) / m²	VAd	127,31
	Wet floor	(U$) / m²	VAw	125,08
	External perimeter	(U$) / m	VPE	328,80
	Dry internal perimeter	(U$) / m	VPd	105,60
	Wet internal perimeter	(U$) / m	VPw	159,70
	Cost of the layout solution			
	Cost/m²	(U$) / m²	VGL	440,30
	Total cost	TVL (U$)	51695,81	
Target layout	Variable	Unit	Abbreviate	Value
	Useful Area	m²	AA	125,00
	Geometric qualification	value	QQA	19,50

Layout Indexes	Abbreviate	Value
Form Factor	FF	5,08
Externalization	IE	1,96
Spaciousness	IA	10,84
Internal Configuration	IP	7,70
Circulation	IC	0,30
Confinement	IR	0,00

Layout codification	
Formation	2 2 15 508 21
Function	UOHT CB1W1B2W2BW KGB4W4
Topology	{[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]}
Space	1174100 1348800 0016685 0004555 0001039 0000300 0000640 0000000

Layout evaluation	Unit	Abbreviate	Value
Geometric qualification	value	QQL	20,20
Nominal Area	m²	AN	138,96
Cost of geometric qualification (TVL / IQL)	(U$) / IQL	VQL	2559,14
Cost of nominal area (TVL / AN)	(U$) / m²	VAN	372,02

58122 2 2 15 508 21 UOHT CB1W1B2W2BW KGB4W4 {[→U→(OHT)] ϵ [C→(B1W1B2→(W2)B→(W))] ϵ [K→(G→(B4W4))]} 1174100 1348800 0016685 0004555 0001039 0000300 0000640 0000000

5.2 Case study genetic strategy

The case study process provides a rich source of information and knowledge retrieval and can incorporate technical resources to support or enhance creativity. It expands the domain in the design process from the perspective of surpassing the expected solution represented by the "best combination – best design." As well as it can be considered as a way to encourage the curiosity and creativity of students, to overcome themselves in the solution of the problem (Maher and Grace 2017). Through case studies, the connections of experiences can be documented. With the lessons of architectural practice, thus making available cases of successes and failures of the profession. (AIA 2001). The FPL assembly using the case study strategy is structured in a constructed design space (180 FPLs this case), and uses the same approach employed in top-down assembly. The basic difference between the top-down approach and the case study strategy, occurs from the step of establishing the geometric planning, defined by the geometric prototype, and generating the genetic code of the FPL. The case study strategy directly uses the genetic code of this prototype to search and retrieve the best similar case in the design space. It is retrieved through the Gfunction gene, which establishes the functionality of the house, associated with the floor area variable *AU,* revealing its size, and finalized with locating the minimum value of the geometric qualification cost (*VAQ*), defining the best case. Once the similar best case is located, the folder of this case is opened in the design space database, which stores in the ARLE GPS model, the geometric planning/ARLE GPS spreadsheet, and the CAD drawing. The geometric prototype of the candidate case is then used to assist the student in modeling the topological design solution by reworking the retrieved CAD drawing, or by modeling the design directly in CAD. With the option for the

student to consult and retrieve other similar cases, to retrieve different assumptions used in the design solutions. It uses the continuous simulation model between geometric planning and topological assembly of the design, until the solution that meets the design requirements is captured, shown in figure 05.

The modeling and design of the candidate FPL to solve the proposed problem using the case study strategy is exemplified by the design of FPL 018 presented by student 18 (figure 06).

Similar to the process used in the top-down approach, the student defines the program, performs geometric prototype assembly of the FPL using the family 7 room dimension value space, and evaluates its geometric qualification using ARLE GPS in a continuous simulation process using the systematic exploration and coevolution model (figure 05) until establishing/obtaining a geometric prototype that meets the demands of the problem. The geometric prototype is defined in the case of FPL 018 by the maximum values (area and perimeter) of the FBPWK rooms, average values of the UCB1B2GS rooms, and minimum values of the W1W4 rooms. This prototype computes the value of the useful area *AU* = 121.36 m², which meets the required value of the useful area (*AU*) of the apartment, and the geometric qualification *QQL*= 19.73, in relation to target values, as shown in table 06.

Table 06 - Geometric prototype - student 018

018	Identification			Geometric prototype - Student 18													2	Apartments / floor (Nf)	Entries (Ne)	2
Layout	Sector	code	Room Functional spaces	Width Wi (m)	Length Lg (m)	Area Au (m^2)	Perimeter Pu (m)	Empty perimeter Pp (m)	Circulation perimeter Pc (m)	Confined perimeter Pr (m)	Floor Dry (Ad)	Floor Wet (Aw)	Perimeter Dry (Pd)	Perimeter Wet (Pw)			Geometric variables	Variable	Unit	Abbreviate	Value
Functions and Dimentions	Social Zone	E1	entrance 1															Total Area	m²	AT	121,36
		U	living & dining	3,26	9,13	29,75	24,78				x		x					External perimeter	m	PE	39,88
		L	living															Condominium perimeter	m	PX+PY	14,10
		D	dining															Symmetry perimeter	m		
		O	home office															Layout figure vertices	u	LV	19
	24,5 %	H	home theater														Cost (euros)	Variable	Unit	Abbreviate	Value
		T	toilet															Dry floor	(U$) / m²	VAd	127,31
	Intimate zone	C	circulation	1,00	4,25	4,25	10,50		x		x		x					Wet floor	(U$) / m²	VAw	125,08
		F	family room	3,00	3,60	10,80	13,20				x		x					External perimeter	(U$) / m	VPE	328,80
		B1	bedroom 1	2,51	3,89	9,76	12,80				x		x					Dry internal perimeter	(U$) / m	VPd	105,60
		W1	bath 1	1,31	2,49	3,26	7,60					x		x				Wet internal perimeter	(U$) / m	VPw	159,70
		B2	bedroom 2	2,72	4,23	11,51	13,90				x		x					Cost of the layout solution			
		W2	bath 2															Cost/m²	(U$) / m²	VGL	411,55
		B	master bedroom	2,45	5,89	14,43	16,68				x		x					Total cost	TVL (U$)	49945,22	
	53,4 %	P	closet			5,39	12,00				x		x				Target layout	Variable	Unit	Abbreviate	Value
		W	master bath	1,37	3,97	5,44	10,68					x		x				Useful Area	m²	AA	125,00
	Service zone	K	kitchen	2,43	6,32	15,36	17,50					x		x				Geometric qualification	value	QQA	19,50
		M	meal room																		
		G	laundry	1,79	3,68	6,59	10,94					x		x							
		S	store room	1,56	2,10	3,28	7,32				x		x								
		B4	bedroom 4																		
	22,1 %	W4	bath 4	1,09	1,41	1,54	4,78					x		x							
		E2	entrance 2																		
	Total					121,36	162,68	0,00	10,50	0,00	89,17	32,19	111,10	51,50							

Layout Indexes	Abbreviate	Value
Form Factor	FF	4,90
Externalization	IE	1,81
Spaciousness	IA	11,02
Internal Configuration	IP	7,38
Circulation	IC	0,48
Confinement	IR	0,00

Layout codification	
Formation	2 2 13 490 19
Function	U CFB1W1B2BPW KGSW4
Topology	{[→U] ϵ [C→(FB1W1B2B→(PW))] ϵ [K→(G→(SW4))]}
Space	1213600 1213600 0016268 0003988 0001410 0000000 0001050 0000000

Layout evaluation	Unit	Abbreviate	Value
Geometric qualification	value	QQL	19,73
Nominal Area	m²	AN	129,54
Cost of geometric qualification (TVL / IQL)	(U$) / IQL	VQL	2531,00
Cost of nominal area (TVL / AN)	(U$) / m²	VAN	385,55

61499 2 2 13 490 19 U CFB1W1B2BPW KGSW4 {[→U] ϵ [C→(FB1W1B2B→(PW))] ϵ [K→(G→(SW4))]} 1213600 1213600 0016268 0003988 0001410 0000000 0001050 0000000

Thus, established the geometric prototype of the FPL, the design space of the FPLs of family seven is explored, in the search for similar cases, through the Gfunction gene U CFB1W1B2BPW KGSW4 being

located the FPL 167, as the best similar case, as shown in table 07. The file FPL 167 (figure 07) in CAD format is then retrieved from the database and leveraged for the solution of the proposed problem (design). And the results as a solution to the problem, FPL 18, are shown in figure 06 and table 07.

The design space of the FPLs solved by the students is shown in table 08, with their geometric *QQL* qualification displayed in figure 08; the composition of the qualification indices, geometric and monetary cost and cost/quality are shown in table 09, and the digital signature of FPLs is displayed in table 10.

Table 07 - FPL student 018

018	Identification			FPL Student 18											
Layout	Sector	code	Room Functional spaces	Width Wi (m)	Length Lg (m)	Area Au (m^2)	Perimeter Pu (m)	Empty perimeter Pp (m)	Circulation perimeter Pc (m)	Confined perimeter Pr (m)	Floor Dry (Ad)	Floor Wet (Aw)	Perimeter Dry (Pd)	Perimeter Wet (Pw)
Functions and Dimentions	Social Zone	E1	entrance 1											
		U	living & dining			31,40	25,42				x		x	
		L	living											
		D	dining											
		O	home office											
	25,7 %	H	home theater											
		T	toilet											
	Intimate zone	C	circulation	1,00	4,20	4,20	10,40		x		x		x	
		F	family room	2,70	4,80	12,96	15,00				x		x	
		B1	bedroom 1	3,05	3,22	9,82	12,54				x		x	
		W1	bath 1	1,30	2,60	3,38	7,80					x		x
		B2	bedroom 2	3,22	3,75	11,25	13,94				x		x	
		W2	bath 2											
		B	master bedroom			13,43	19,50				x		x	
	54,3 %	P	closet			6,28	10,93				x		x	
		W	master bath			4,97	9,78					x		x
	Service zone	K	kitchen			14,09	16,20					x		x
		M	meal room											
		G	laundry	1,80	2,95	5,31	9,50					x		x
		S	store room	1,80	1,80	3,24	7,20				x		x	
		B4	bedroom 4											
	20,0 %	W4	bath 4	1,00	1,80	1,80	5,60					x		x
		E2	entrance 2											
	Total					122,13	163,81	0,00	10,40	0,00	92,58	29,55	114,93	48,88

2	Apartments / floor (Nf)	Entries (Ne)	2
Geometric variables	Variable	Unit	Abbreviate	Value
	Total Area	m²	*AT*	139,08
	External perimeter	m	*PE*	38,25
	Condominium perimeter	m	*PX*	10,95
	Symmetry perimeter	m	*PY*	7,82
	Layout figure vertices	u	*LV*	14
Cost (euros)	Variable	Unit	Abbreviate	Value
	Dry floor	(U$) / m²	*VAd*	127,31
	Wet floor	(U$) / m²	*VAw*	125,08
	External perimeter	(U$) / m	*VPE*	328,80
	Dry internal perimeter	(U$) / m	*VPd*	105,60
	Wet internal perimeter	(U$) / m	*VPw*	159,70
	Cost of the layout solution			
	Cost/m²	(U$) / m²	*VGL*	402,51
	Total cost	TVL (U$)	49158,14	
Target layout	Variable	Unit	Abbreviate	Value
	Useful Area	m²	*AA*	125,00
	Geometric qualification	value	*QQA*	19,50

Layout Indexes	Abbreviate	Value
Form Factor	*FF*	4,83
Externalization	*IE*	1,62
Spaciousness	*IA*	11,05
Internal Configuration	*IP*	7,41
Circulation	*IC*	0,47
Confinement	*IR*	0,00

Layout codification	
Formation	2 2 13 484 14
Function	U CFB1W1B2BPW KGSW4
Topology	{[→U] ϵ [C→(FB1W1B2B→(PW))] ϵ [K→(G→(SW4))]}
Space	1221300 1390800 0016381 0003825 0001095 0000782 0001040 0000000

Layout evaluation	Unit	Abbreviate	Value
Geometric qualification	value	*QQL*	19,61
Nominal Area	m²	*AN*	127,20
Cost of geometric qualification (TVL / IQL)	(U$) / IQL	*VQL*	2506,31
Cost of nominal area (TVL / AN)	(U$) / m²	*VAN*	386,46

62267 2 2 13 484 14 U CFB1W1B2BPW KGSW4 {[→U] ϵ [C→(FB1W1B2B→(PW))] ϵ [K→(G→(SW4))]} 1221300 1390800 0016381 0003825 0001095 0000782 0001040 0000000

Table 08 - FPLs qualification value space – students

Geometric Index	Abreviate	Minimum	Maximum	Average	Standard deviation
Form	*FF*	4,38	5,87	5,02	0,42
Vertice	*V*	6	32	15,8	4,97
Configuration	*IP*	6,90	8,31	7,41	0,32
Externalization	*IE*	1,45	2,55	2,00	0,25
Circulation	*IC*	0	0,77	0,41	0,14
Confinement	*IR*	0	0,59	0,36	0,12
Qualification	*QQL*	19,50	20,65	19,93	0,35
Qualification125	*QQL125*	19,57	20,80	20,07	0,37
Cost/m² (U$)	*VGL*	393,03	463,62	435,22	17,36
Cost qualification (U$)	*VQL*	2454,57	2781,25	2666,79	78,05
Cost qualification (*AU/QQL*)	*VAQ*	58848	63451	61314	1543

Table 09 - FPLs' variables – students

ID	*AU*	*AT*	*FF*	*LV*	*IE*	*IA*	*IP*	*IC*	*IR*	*QQL*	*QQL125*	*CLQ*	*AN*	*LOSS*	*VGL*	*VQL*	*VAQ*
1	122,37	139,41	5,87	21	2,55	11,06	7,04	0	0	20,65	20,80	1	145,32	22,95	461,43	2734,13	59259
2	120,18	137,75	5,52	16	2,24	10,96	7,79	0,77	0,45	19,77	20,03	11	125,24	5,06	457,52	2781,25	60789
3	123,44	138,26	4,63	10	2,01	11,11	7,41	0,41	0,24	19,87	19,95	14	130,60	7,16	436,04	2708,83	62124
4	120,83	139,18	4,76	16	2,15	10,99	8,31	0,49	0,49	20,47	20,70	2	139,77	18,94	463,62	2737,60	59028
5	124,37	142,42	4,44	14	1,85	11,15	7,47	0,37	0,33	19,78	19,81	18	129,80	5,43	427,15	2685,84	62877
6	118,05	134,88	5,08	21	1,96	10,87	7,53	0,29	0	20,06	20,45	6	128,52	10,47	440,84	2594,52	58848
7	123,59	140,73	4,92	17	1,78	11,12	7,36	0,42	0,30	19,54	19,61	24	124,35	0,76	422,00	2669,13	63250
8	120,04	136,3	5,13	12	2,09	10,96	7,29	0,44	0	19,89	20,16	9	127,39	7,35	443,73	2677,99	60352
9	118,63	135,88	4,70	17	2,03	10,89	7,84	0,28	0,36	20,13	20,48	5	130,50	11,87	456,50	2690,24	58932
10	124,85	142,31	5,32	18	2,29	11,17	7,36	0,43	0	20,40	20,41	7	142,95	18,10	445,35	2725,60	61201
11	123,88	140,83	4,44	6	1,45	11,13	7,43	0,44	0	19,56	19,62	23	125,03	1,15	401,56	2543,16	63333
12	124,53	141,43	4,49	12	1,76	11,16	7,35	0,33	0	19,94	19,97	13	133,15	8,62	393,04	2454,57	62452
13	123,73	141,34	4,77	10	2,03	11,12	7,05	0,45	0,25	19,50	19,57	25	123,73	0,00	429,18	2723,19	63451
14	123,19	143,54	5,84	21	2,40	11,1	7,28	0,27	0	20,52	20,62	4	143,55	20,36	454,84	2730,56	60034
15	124,48	140,17	5,60	14	2,05	11,16	7,06	0,33	0	19,94	19,97	12	133,10	8,62	426,08	2659,86	62427
16	119,88	136,12	4,94	17	1,92	10,95	7,75	0,66	0	19,96	20,24	8	128,57	8,69	435,86	2617,82	60060
17	122,83	141,46	4,38	18	1,60	11,08	7,9	0,34	0,59	19,66	19,78	20	125,88	3,05	417,18	2606,45	62477
18	122,13	139,08	4,83	14	1,62	11,05	7,41	0,47	0	19,61	19,76	21	124,21	2,08	408,96	2546,43	59505
19	124,32	140,75	4,90	14	1,97	11,15	7,34	0,43	0	19,63	19,67	22	126,82	2,50	435,11	2755,65	63332
20	121,60	141,40	5,05	16	2,01	11,03	7,09	0,46	0	19,66	19,84	17	124,62	3,02	433,25	2679,72	61851
21	120,92	136,79	5,09	18	2,15	11,00	6,90	0,45	0	19,59	19,81	19	122,60	1,68	424,90	2622,72	61725
22	118,72	135,32	4,82	11	1,95	10,9	7,08	0,37	0	19,56	19,90	16	119,82	1,10	424,58	2577,03	60695
23	123,36	140,09	5,43	32	2,22	11,11	7,56	0,34	0	20,54	20,63	3	144,17	20,81	452,81	2719,51	60058
24	124,33	141,53	5,34	14	1,99	11,15	7,33	0,33	0,25	19,90	19,94	15	132,14	7,81	431,23	2694,18	62477
25	124,95	142,29	5,22	16	2,15	11,18	7,27	0,55	0	20,05	20,05	10	135,82	10,87	437,74	2727,89	62319

Where: *QQL*125 - geometric qualification on the base *AA* =125m²; *CLQ* = *QQL*125 geometric qualification rating; *CLC*= *VGL* cost rating; *CLV* = *VQL* cost/quality rating; *VAQ* = geometric qualification cost.

The FPL design solution process using the ARLE GPS tool is supported in the present case by the existent design space (180 FPLs), its respective value space, and response surfaces. In the case of the non-existence of a design space and consequently its value space, this process can be executed using the top-down approach by adopting an FPL design that meets the required quality. For example, the target FPL design 167, which defines as target indices (configuration - *IC*=7.13; exteriorization - *IE*=1.82; circulation - *IC*=0.51; confinement - *IR* = ZERO; form factor - *FF*=5.00; number of vertices - *LV*=17). Under these conditions the candidate FPL designs will be evaluated against the performance of FPL 167.

Table 10 - Digital Signature of FPLs - students

FPL	VAQ	Gform	Gfunction	Gspace
001	59259	2 2 13 588 21	UT FB1W1B2BPW KGB4W4	1223700 1394100 0015568 0006030 0000710 0000195 0000000 0000000
002	60789	2 2 16 552 16	E1UHT CFB1W1B2BW KGSB4W4	1201800 1377500 0017071 0005265 0000603 0000605 0001695 0000978
003	62124	2 2 14 463 10	CB1W1B2W2BW KGSB4W4	1234400 1382600 0016467 0004721 0000719 0000000 0000920 0000540
004	59028	2 2 18 478 16	E1UOT CFB1W1B2BPW KMGSB4W4	1208300 1386600 0018842 0005065 0000555 0000000 0001670 0001080
005	62877	2 2 13 444 14	LDT CB1W1B2BW KGB4W4	1243700 1424200 0016668 0004426 0000871 0000000 0000820 0000730
006	58848	2 2 15 508 21	UOHT CB1W1B2W2BW KGB4W4	1180500 1348800 0016355 0004555 0001039 0000300 0000640 0000000
007	63250	2 2 15 493 17	E1UOHT CB1W1B2BW KGSW4	1235900 1407300 0016375 0004217 0001185 0000439 0000934 0000662
008	60352	2 2 14 513 12	UOT CFB1W1B2BW KGSW4	1200400 1363000 0015980 0004870 0001115 0000000 0000970 0000000
009	58932	2 2 16 471 17	UOHT CB1W1B2W2BPW KGB4W4	1186300 1358800 0017088 0004738 0000744 0000000 0000610 0000776
010	61201	2 2 15 533 18	UOHT CB1W1B2BW KGSB4W4	1248500 1423100 0016450 0005470 0000880 0000000 0000950 0000000
011	63333	2 2 14 444 06	UOHT CB1W1B2BW KGB4W4	1238800 1408300 0016536 0003438 0001289 0000540 0000986 0000000
012	62452	2 2 12 449 12	LD CB1W1B2BW KGB4W4	1245300 1414300 0016400 0004180 0000640 0000515 0000730 0000000
013	63451	2 2 13 478 10	UT CFB1W1B2BW KGSW4	1237300 1413400 0015690 0004825 0000850 0000000 0001010 0000560
014	60034	2 2 14 585 21	UO CFB1W1B2BW KGSB4W4	1231900 1435400 0016171 0005755 0000765 0000480 0000590 0000000
015	62427	2 2 12 560 14	UT CB1W1B2BPW KGS	1244800 1401700 0015746 0004864 0001050 0000715 0000726 0000000
016	60060	2 2 13 494 17	UOH CB1W1B2BW KGSW4	1198800 1361200 0016970 0004476 0000987 0000300 0001445 0000000
017	62477	2 2 17 438 18	E1UHT CB1W1B2W2BPW KGSB4W4	1228300 1414600 0017512 0003810 0000465 0000930 0000750 0001305
018	59505	2 2 13 484 14	U CFB1W1B2BPW KGSW4	1221300 1390800 0016381 0003825 0001095 0000782 0001040 0000000
019	63332	2 2 15 490 14	UHT CB1W1B2W2BW KGSB4W4	1243200 1407500 0016360 0004680 0001130 0000000 0000956 0000887
020	61851	2 2 13 506 16	UO CFB1W1B2W2BW KGW4	1216000 1411000 0015640 0004770 0001230 0000000 0001020 0000000
021	61725	2 2 13 509 18	E1U CB1W1B2BW KGSB4W4	1209200 1367900 0015170 0005035 0000917 0000000 0001000 0000000
022	60695	2 2 13 483 11	UOHT CB1W1B2BPW KG	1187200 1353200 0015439 0004526 0000720 0000365 0000798 0000000
023	60058	2 2 17 544 32	E1UOHT CB1W1B2W2BPW KGSW4	1233600 1400900 0016789 0005250 0000955 0000225 0000763 0000000
024	62477	2 2 14 535 14	UT CFB1W1B2BPW KGB4W4	1243300 1415300 0016355 0004744 0001178 0000435 0000730 0000552
025	62319	2 2 14 522 16	UOT CB1W1B2BW KGSB4W4	1249500 1422900 0016255 0005125 0001101 0000000 0001220 0000000

6. Design Space

The design space (Woodbury and Burrow 2006; Akin 2006; Goldschmidt 2006; Kannengiesser and Gero 2017; Davis and Gristwood 2018; Wortmann 2018; Maeng and Hyun 2021) explored, is established by a population of 180 apartment FPLs, with the typology of two, four, or eight units per floor; one or two accesses with their external environment; number of rooms ranging from nine to fifteen; floor area ranging from 52.70 to 149.11 m²; functional classification of three bedrooms. Representatives of the planned apartment population, built and commercialized in several cities in Brazil, at the end of the 20th century and beginning of the 21st century. The result of this processing is presented in Fig. 02 and shows the behavior of the apartments' performance captured by eight families of geometrically qualified FPLs. Six families of FPLs are statistically defined according to their geometric qualification, and two families that define the boundary regions of low and high qualification are statistically estimated, according to the explored design space. The database of the design space dedicated to problem-based learning (PBL) in the present case makes available to students thirty cases of high-performance FPLs, belonging to family seven.

7. Value Space

The optimization model is established by ARLE GPS through the value space of design space, which defines the boundaries of the geometric qualification of the FPLs , in an analogy to house performance. It solves the question of searching and directing the candidate solution to the specific region of the value space that accommodates the high-quality solutions. It thus achieves the goal of configuring and constraining the solution space and constructing a performance measure, conceptualized as a wicked question of the design problem (Wortmann et al. 2015; Davis and Gristwood 2016b; Davis and Gristwood

2018). Statistical processing of the design space variables makes it possible to establish a value space of the FPLs of family seven, which are defined by the indices of the geometric qualification *QQL*: *IC*- configuration, *IE*- exteriorization, *IC*- circulation and *IR*- confinement; and by the FPL formation variables: form factor *FF* and number of vertices *LV*. Also included in this case study are the *VGL* cost, *VQL* qualification cost and *AN* loss geometric cost (table 11), and the digital signature of FPLs is displayed in table 12. The analysis of this value space of family seven, allows the conclusion that the geometric planning of a FPL that presents the geometric qualification indices situated in the region of the value space defined by the average value, and all the non-confined living environments, defines a geometric solution of the FPL whose apartment performance is situated in the high-performance region. The room dimension value space is computed by statistically processing the area and perimeter values of the rooms, in relation to the demarcation of their boundaries: minimum and maximum, average value, and the form factor of the polygons defining the rooms. This space of geometric values of the rooms assists students to run simulations repetitively, in real time, and evaluate the geometric qualification of the FPL in an analogy to the performance of the house, to students establish an initial geometric dimensioning of the FPL.

Table 11 - Variables of FPLs - Family 7

FPL	*AU*	*AT*	*FF*	*LV*	*IE*	*IP*	*IC*	*IR*	*QQL*	*QQL125*	*AN*	*LOSS*	*VGL*	*VQL*	*VAQ*
132	101,01	117,99	5,15	18	1,86	6,82	0,36	0,00	18,37	19,72	104,50	3,49	445,49	2449,59	54986
134	101,7	116,21	4,55	19	1,85	6,98	0,49	0,26	18,16	19,45	100,96	-0,74	427,21	2423,23	56002
135	101,81	120,11	4,7	22	1,84	7,05	0,3	0,63	18,15	19,43	100,79	-1,02	450,51	2527,08	56094
136	102,10	117,06	4,38	11	1,75	7,01	0,84	0,00	18,02	19,28	98,64	-3,46	439,84	2492,08	56659
138	103,51	117,97	4,53	14	1,78	6,63	0,49	0,00	18,09	19,26	99,80	-3,71	425,88	2436,86	57219
142	104,68	119,37	4,83	21	2,00	6,82	0,78	0,00	18,27	19,38	102,81	-1,87	442,35	2534,50	57296
143	104,90	119,78	4,94	27	1,91	6,88	0,37	0,31	18,35	19,45	104,16	-0,74	443,85	2537,30	57166
148	106,58	122,22	5,19	12	2,13	7,18	0,60	0,63	18,40	19,40	105,02	-1,56	458,58	2684,46	57924
151	107,60	123,99	4,27	9	1,77	7,15	0,87	0,39	18,04	18,96	98,97	-8,63	426,37	2591,79	59645
152	107,95	123,10	4,89	15	1,93	6,84	0,41	0,56	18,18	19,09	101,29	-6,66	442,40	2626,92	59378
153	108,01	124,02	5,25	19	1,84	6,84	0,47	0,00	18,59	19,52	108,30	0,29	433,37	2517,96	58101
154	108,48	124,02	5,34	19	1,84	6,96	0,46	0,00	18,76	19,67	111,30	2,82	413,50	2391,04	57825
155	108,7	129,79	5,1	14	1,69	6,85	0,75	0	18,21	19,08	101,80	-6,90	423,45	2527,68	59692
158	109,61	125,45	4,82	22	1,97	7,45	0,46	0,57	18,86	19,70	113,09	3,48	454,12	2639,27	58118
159	110,21	121,42	4,98	12	1,83	6,82	0,33	0	18,82	19,63	112,37	2,16	424,18	2483,98	58560
161	110,54	121,88	4,59	29	1,48	7,1	0,42	0	18,68	19,46	109,88	-0,66	412,62	2441,72	59176
163	110,87	125,08	4,63	18	1,63	7,59	0,82	0,77	18,16	18,90	100,96	-9,91	434,62	2653,45	61052
165	111,68	129,89	5,08	14	1,69	7,13	0,49	0	18,89	19,61	113,63	1,95	423,68	2504,84	59121
166	112,45	129,81	5,63	18	2,04	7,57	0,88	0,55	18,68	19,35	109,88	-2,57	454,70	2770,75	60198
167	113,98	130,05	5,00	17	1,82	7,09	0,51	0,00	19,07	19,67	116,91	2,93	423,96	2533,95	59769
169	115,35	133,19	4,36	18	1,60	6,78	0,36	0,38	18,38	18,88	104,67	-10,68	404,17	2536,53	62758
171	118,87	135,13	4,92	14	1,83	6,00	0,45	0,00	18,97	19,29	115,08	-3,79	408,64	2560,62	62662
172	118,95	136,68	5,57	28	2,13	7,28	0,62	0,63	19,04	19,36	116,36	-2,59	445,13	2780,90	62474
174	119,50	135,28	4,69	12	1,78	6,73	0,48	0,26	18,72	19,00	110,59	-8,91	406,00	2591,72	63835
175	119,52	134,92	4,37	9	1,58	6,91	0,58	0,67	18,18	18,45	101,29	-18,23	398,01	2616,60	65743
176	121,08	138,58	5,22	26	1,90	7,37	0,77	0,29	19,22	19,43	119,69	-1,39	467,60	2945,75	62997
177	126,01	142,87	4,68	12	1,65	7	0,49	0,7	18,68	18,63	109,88	-16,13	431,50	2910,76	67457
178	127,06	146,17	5,31	18	1,73	7,41	0,66	0,25	19,51	19,40	125,19	-1,87	420,07	2735,71	65126
179	143,16	160,07	4,32	12	1,52	6,96	0,58	0,56	19,30	18,45	121,19	-21,97	368,83	2735,83	74176
180	149,11	167,81	5,02	16	1,84	7,37	0,7	0,29	20,44	19,27	143,96	-5,15	401,08	2925,89	72950

Where: *QQL*125 - geometric qualification on the base *AA* =125m²; *CLQ* = *QQL*125 geometric qualification rating; *CLC* = *VGL* cost rating; *CLV* = *VQL* cost/quality rating; *VAQ* = geometric qualification cost.

Table 12 - FPL digital signature – family seven

FPL	AU	AT	FF	LV	IE	IP	IC	IR	QQL	QQL125	AN	LOSS	VGL	VQL	VAQ
132	101,01	117,99	5,15	18	1,86	6,82	0,36	0,00	18,37	19,72	104,50	3,49	445,49	2449,59	54986
134	101,7	116,21	4,55	19	1,85	6,98	0,49	0,26	18,16	19,45	100,96	-0,74	427,21	2423,23	56002
135	101,81	120,11	4,7	22	1,84	7,05	0,3	0,63	18,15	19,43	100,79	-1,02	450,51	2527,08	56094
136	102,10	117,06	4,38	11	1,75	7,01	0,84	0,00	18,02	19,28	98,64	-3,46	439,84	2492,08	56659
138	103,51	117,97	4,53	14	1,78	6,63	0,49	0,00	18,09	19,26	99,80	-3,71	425,88	2436,86	57219
142	104,68	119,37	4,83	21	2,00	6,82	0,78	0,00	18,27	19,38	102,81	-1,87	442,35	2534,50	57296
143	104,90	119,78	4,94	27	1,91	6,88	0,37	0,31	18,35	19,45	104,16	-0,74	443,85	2537,30	57166
148	106,58	122,22	5,19	12	2,13	7,18	0,60	0,63	18,40	19,40	105,02	-1,56	458,58	2684,46	57924
151	107,60	123,99	4,27	9	1,77	7,15	0,87	0,39	18,04	18,96	98,97	-8,63	426,37	2591,79	59645
152	107,95	123,10	4,89	15	1,93	6,84	0,41	0,56	18,18	19,09	101,29	-6,66	442,40	2626,92	59378
153	108,01	124,02	5,25	19	1,84	6,84	0,47	0,00	18,59	19,52	108,30	0,29	433,37	2517,96	58101
154	108,48	124,02	5,34	19	1,84	6,96	0,46	0,00	18,76	19,67	111,30	2,82	413,50	2391,04	57825
155	108,7	129,79	5,1	14	1,69	6,85	0,75	0	18,21	19,08	101,80	-6,90	423,45	2527,68	59692
158	109,61	125,45	4,82	22	1,97	7,45	0,46	0,57	18,86	19,70	113,09	3,48	454,12	2639,27	58118
159	110,21	121,42	4,98	12	1,83	6,82	0,33	0	18,82	19,63	112,37	2,16	424,18	2483,98	58560
161	110,54	121,88	4,59	29	1,48	7,1	0,42	0	18,68	19,46	109,88	-0,66	412,62	2441,72	59176
163	110,87	125,08	4,63	18	1,63	7,59	0,82	0,77	18,16	18,90	100,96	-9,91	434,62	2653,45	61052
165	111,68	129,89	5,08	14	1,69	7,13	0,49	0	18,89	19,61	113,63	1,95	423,68	2504,84	59121
166	112,45	129,81	5,63	18	2,04	7,57	0,88	0,55	18,68	19,35	109,88	-2,57	454,70	2770,75	60198
167	113,98	130,05	5,00	17	1,82	7,09	0,51	0,00	19,07	19,67	116,91	2,93	423,96	2533,95	59769
169	115,35	133,19	4,36	18	1,60	6,78	0,36	0,38	18,38	18,88	104,67	-10,68	404,17	2536,53	62758
171	118,87	135,13	4,92	14	1,83	6,00	0,45	0,00	18,97	19,29	115,08	-3,79	408,64	2560,62	62662
172	118,95	136,68	5,57	28	2,13	7,28	0,62	0,63	19,04	19,36	116,36	-2,59	445,13	2780,90	62474
174	119,50	135,28	4,69	12	1,78	6,73	0,48	0,26	18,72	19,00	110,59	-8,91	406,00	2591,72	63835
175	119,52	134,92	4,37	9	1,58	6,91	0,58	0,67	18,18	18,45	101,29	-18,23	398,01	2616,60	65743
176	121,08	138,58	5,22	26	1,90	7,37	0,77	0,29	19,22	19,43	119,69	-1,39	467,60	2945,75	62997
177	126,01	142,87	4,68	12	1,65	7	0,49	0,7	18,68	18,63	109,88	-16,13	431,50	2910,76	67457
178	127,06	146,17	5,31	18	1,73	7,41	0,66	0,25	19,51	19,40	125,19	-1,87	420,07	2735,71	65126
179	143,16	160,07	4,32	12	1,52	6,96	0,58	0,56	19,30	18,45	121,19	-21,97	368,83	2735,83	74176
180	149,11	167,81	5,02	16	1,84	7,37	0,7	0,29	20,44	19,27	143,96	-5,15	401,08	2925,89	72950

8. Response Surface (Rsm)

The gauging of the positioning of the response variables (performance) through the response surface method aims to know the behavior of a given variable, to move the response to its maximization region, to optimize the candidate solution. (Martins 2000; Papalambros and Wild 2000, p.44–49; Kleijnen 2015 p.81–82; Díaz-Manríquez et al. 2016). In this way are captured relationships between the input variables, defined by the floor area *AU* and geometric qualification *QQL* of the FPLs of family seven, and the output variables established by the form factor, and number of vertices of the FPL polygon; to gain insights regarding these relationships.

8.1 Response surface of the FF form factor

The form factor defines the format of the FPL polygon. The simulation of *FF* from the design space using the response surface method (RSM) shown in Fig. 09, aims to capture a description of the format of the FPL polygon. This description assists the student in assembling the FPL structure, since it allows him to assemble and model the FPL structure with a reference of the artifact format. As an example, the *FF* value computed by RSM for FPL 006 is equal to 4.90, and in this case the student already knows that the format of the polygon must be very different from a square or a rectangle, since the value is far from 4.00, and the simulation of the number of vertices by RSM points to a format of the FPL polygon with 19 vertices/sides. The student is also supported in this case by the exploration of the design space, through *FF*, a condition that enables the student, to know design solutions with similar shapes.

8.2 Response Surface of the Number of Vertices

The *FF* form factor is measured by the perimeter/√area ratio. It makes it possible to establish a benchmark of the FPL polygon form, as well as to compare different formats. A square polygon this value equal to 4.0, and a rectangle displays a value greater than 4.0. However, different polygon forms can compute equal *FF* values. For example, a rectangle that has the width:length ratio equal to 1:3 computes an *FF* value of 4.62, equal to the *FF* value of an L-shaped polygon with equal sides that has the ratio 1:2. One way to differentiate geometrically between the two polygons is by the number of vertices in the polygon. The rectangle sets the number of vertices equal to four, which establishes the number of sides of the rectangular polygon. The "L"-shaped polygon, on the other hand, has six vertices, defining a polygon with six sides. Thus, the number of vertices (*LV*) makes it possible to establish the number of sides of the apartment polygon shown in Fig. 10 (Martins, 1999; Libecap and Lueck 2009).

A point worth highlighted in the ARLE GPS systematic model is the conversion of the *QQL* qualification of FPLs from a database to the same AA qualification base, in this case *QQL*125, through the relation *QQL*125=((*QQL***3)*125/*AU*). Applying this model mechanism, the FPLs planned by the students are compared with the FPLs that make up family seven of the design space. The FPLs generated by the students define *QQA*125 ranging between 19.57 and 20.80, mean 20.09 and *VGL* costs in the range of 393.03 to 463.62, with an average value of $435.22, The FPLs belonging to family 7 in turn present a geometric qualification *QQL*125, ranging between 18.45 and 19.72, mean 19.27 and *VGL* costs in the range of U$ 368.83 to 467.60, with an average value of U$428.39, shown in Tables 08 and 10.

9. Students Performance In Problem Solving

One of the most important aspects of the design process performed by the students using the ARLE GPS tool is the conversion of the wicked problem into a well-defined problem, as shown in this case study. This conversion promotes a change in the problem-solving process, thus enabling the problem to be solved rationally through mathematical modeling of the decision-making problem, rather than a draw method via sketches (Papalambros and Wilde 2000; Archer et al. 2005). The goal of this conversion is to establish the solution to the problem, as a strategic process to propose and evaluate various solution possibilities, achieve optimization, and generate creative designs. Regarding students' performance in this process, Casakin and Wodehouse (2021) emphasize the need to propose criteria for measuring students' creativity in the teaching-learning process of architectural design. A feasible procedure for solving this issue, is to measure the value of a potentially creative artifact, in terms of its attributes of utility (social value of the artifact/actual use) and performance (conformity to the intended application). However, from the literature review in the design field, no direct measure of utility or performance was found (Sarkar and Chakrabarti 2011; Maher and Fisher 2012; Dino 2016). ARLE GPS provides a solution to this issue. The tool primarily aims to optimize the FPL design solution by increasing the geometric qualification of the FPL in an analogy with maximizing the performance of the house, and to decrease the costs of converting the design into a house to achieve minimization of the cost/quality ratio. Objective that qualifies it in the list of tools suitable to operate in the quantitative innovation. (Taura and Nagai 2017). In this way, it acts as a tool that supports creative ideas (Brem et al. 2016). ARLE GPS evaluates the innovation and creativity of the design solution, through the social value of the house

(actual use), computed by meeting the required specifications of the house, in relation to the pre-assigned objective (purpose), and the intended needs and amenities (utility). Quantifying the qualification obtained (*QQL*) in relation to that required (*QQA*), in an analogy with the functionality and behavior of the house (performance). Associated with the evaluation of the usability and harness of the house (utilization), computed by the geometric cost of *AN* losses, indicative of the degree of social satisfaction of the house. Importantly, there were no losses in the student-generated FPL designs, relative to the required targets (*AA* = 125; *QQA* = 19.50), only gains, reaching significant percentages of geometric gain, about nineteen percentage points, as presented in Table 02. Thus, constituting creative designs FPL, which represent qualitative innovations. An important issue to be highlighted in this case study, is that all students solved the proposed problem using the ARLE GPS tool, and presented a performance of the solutions, superior to the required performance of the house, as demonstrated by the geometric qualification *QQL*, and the cost of geometric losses AN. As well as outperforming the high-performance FPLs, constituted by family seven of the design space, as shown in Fig. 08, and with similar cost (*VGL*). Thus, demonstrating the performance of ARLE GPS as a tool that supports students' creative ideas in problem solving. As well as it empowers the use of the students' FPL designs as optimized, innovative, and creative real-world apartment solutions. The process of evaluating students' performance, and creativity in the course discipline, in relation to the present case study/application, is established based on the geometric qualification *QQL* of the FPL design solution, computed on a scale of 0 to 10, and the grades assigned to students range from 9.4 to 10. This process elicits a competition among students towards exceeding the required *QQL* target value, as in a real-world competition process that aims at maximizing the target object. A competitive condition ascertained through the *QQA*125 values shown in Table 11 and Fig. 08.

10. Conclusion

The case study demonstrates the assistance and effectiveness of the GPS ARLE model as an innovative tool acting in the action-decision field of the robust and creative design process. Associated with the problem-based learning (PBL) system and case-based instruction (CBI) model, applied in an architectural studio. ARLE GPS thus allows students to make the design problem of an apartment explicit already in the early design phase, i.e., in the geometric planning phase. ARLE GPS enables students to make the design problem of an apartment explicit already at the early design stage, i.e., at the geometric planning stage. In this way they make the problem clear, and solve it rationally innovative, and creative way, supported by mathematical modeling ARLE GPS, using the top-down FPL structure assembly approach, and the genetic strategy of the case study. Furthermore, they take advantage of an important and unprecedented attribute made available by the tool, which is its ability to assess the cost of design decisions directly and instantaneously through the geometric variables of the FPL. By structuring the geometric prototype of the FPL, which aims to achieve the optimization of the apartment's performance. The construction of the geometric prototype allows the students to perform the modeling process of the topological solution using the representative variables of the rooms, already dimensioned evaluated and optimized, in relation to the required performance, and knowing the order of assembly and connectivity of the rooms in the structure, as well as the format of the figure. Thus, the assistance that the tool provides

to students occurs already at the initial stage of the design spatial planning process. The ARLE GPS biological model represents a great aid to students in the CBI model, due to the tool's functional ability to encode and index the information needed to describe and retrieve the best case from a design space, using a search engine, established by a sophisticated physical biological model. This enables them to learn about a range of attitudes used to solve the design, directly from the code. The code, in turn, provides a set of information and metrics for the analysis and evaluation of FPLs, directly from the genetically encoded design space. The performance of the ARLE GPS tool thus demonstrates its inventive ability to evaluate the innovation and creativity of the FPL design solution through the social value of the house (actual use), and the degree to which it meets the required specifications, based on the assigned needs (utility), and fulfillment of the pre-assigned objective (purpose). Through the response of the geometric qualification evaluation (*QQL*) of the FPL, in relation to the required qualification (*QQA*), in analogy with the performance of the house, and the response of the usability of the house, resulting from its use during its lifetime, computed by the robust design model ARLE GPS, by the geometric cost of losses (*AN*) (satisfaction). And thus fills a gap in the field of architectural design by establishing a process for optimizing the FPL solution and proposing a direct measure of apartment performance and usability. The result obtained in this case study, according to the students' report, in relation to the use and assistance of ARLE GPS in problem solving, was that it provided the opportunity to establish a level of information, reflective practice, competencies, skills and confidence, which allowed the development of design solutions, with a degree of innovation and creativity superior to the FPLs that make up the database of apartments located in the high performance zone of the design space, as shown in Fig. 08. From the instructor teacher's perspective, the ARLE GPS tool fully accomplished the mission of assisting the students in solving the complex problem of planning and designing the FPL of a house. Since all the students solved the proposed problem, and even excelled in the solution.

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Figures

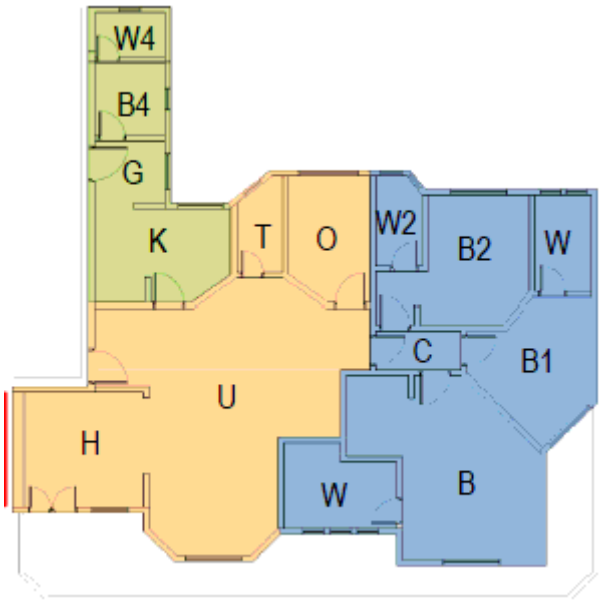

Figure 1

FPL 006

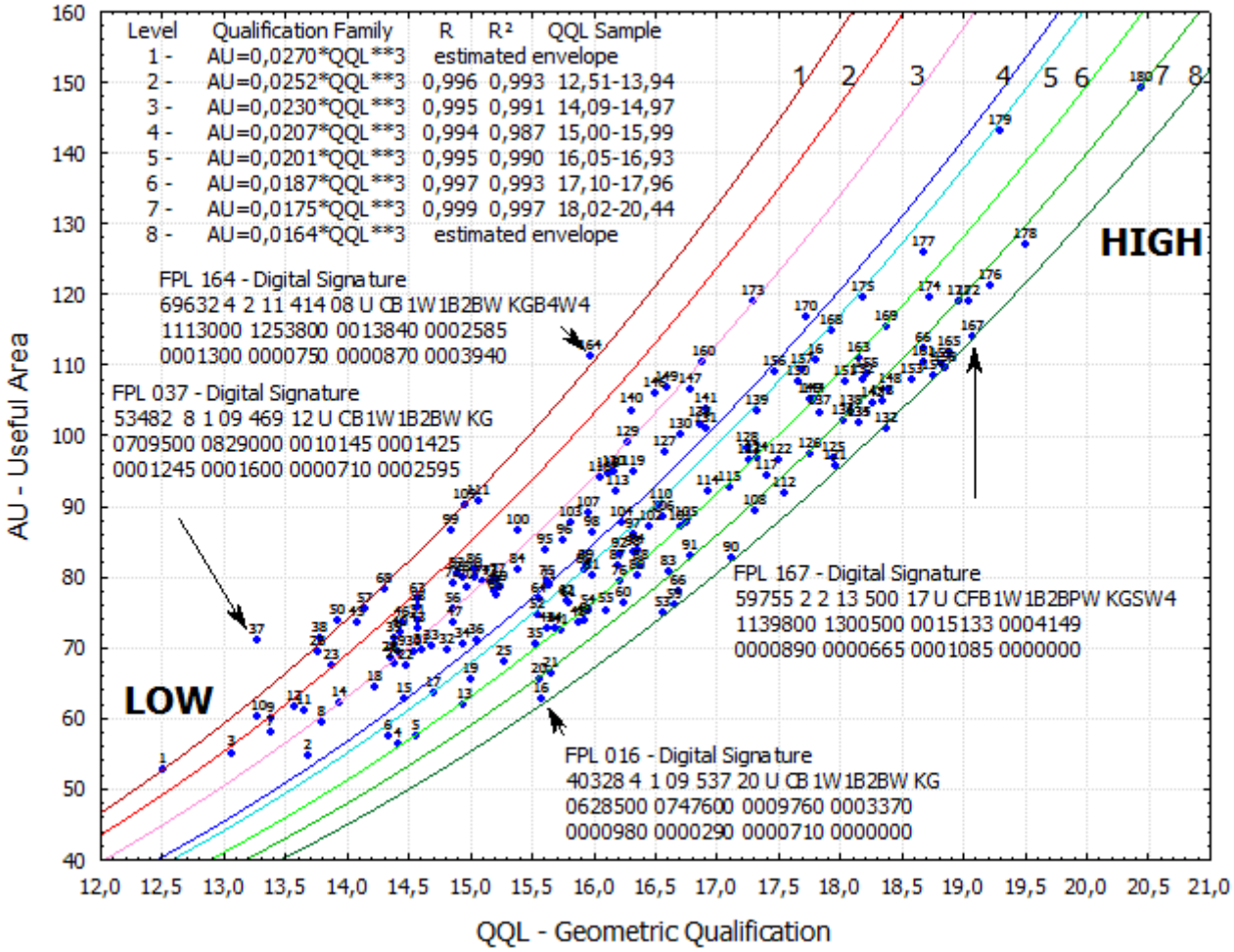
Level Qualification Family R R² QQL Sample
1 - AU=0,0270*QQL**3 estimated envelope
2 - AU=0,0252*QQL**3 0,996 0,993 12,51-13,94
3 - AU=0,0230*QQL**3 0,995 0,991 14,09-14,97
4 - AU=0,0207*QQL**3 0,994 0,987 15,00-15,99
5 - AU=0,0201*QQL**3 0,995 0,990 16,05-16,93
6 - AU=0,0187*QQL**3 0,997 0,993 17,10-17,96
7 - AU=0,0175*QQL**3 0,999 0,997 18,02-20,44
8 - AU=0,0164*QQL**3 estimated envelope
FPL 164 - Digital Signature
69632 4 2 11 414 08 U CB 1W 1B2BW KGB4W4
1113000 1253800 0013840 0002585
0001300 0000750 0000870 0003940
FPL 037 - Digital Signature
53482 8 1 09 469 12 U CB1W 1B2BW KG
0709500 0829000 0010145 0001425
0001245 0001600 0000710 0002595
FPL 167 - Digital Signature
59755 2 2 13 500 17 U CFB1W 1B2BPW KGSW4
1139800 1300500 0015133 0004149
0000890 0000665 0001085 0000000
FPL 016 - Digital Signature
40328 4 1 09 537 20 U CB 1W 1B2BW KG
0628500 0747600 0009760 0003370
0000980 0000290 0000710 0000000
HIGH
LOW
AU - Useful Area
QQL - Geometric Qualification

Figure 2

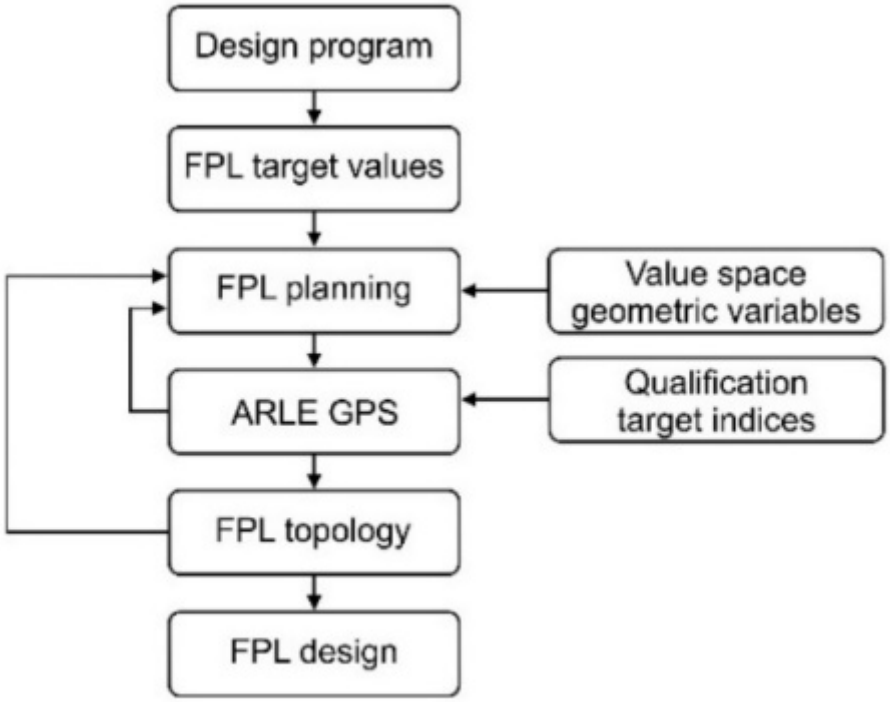

Figure 3

ARLE systematic model of exploration and coevolution - top-down approach

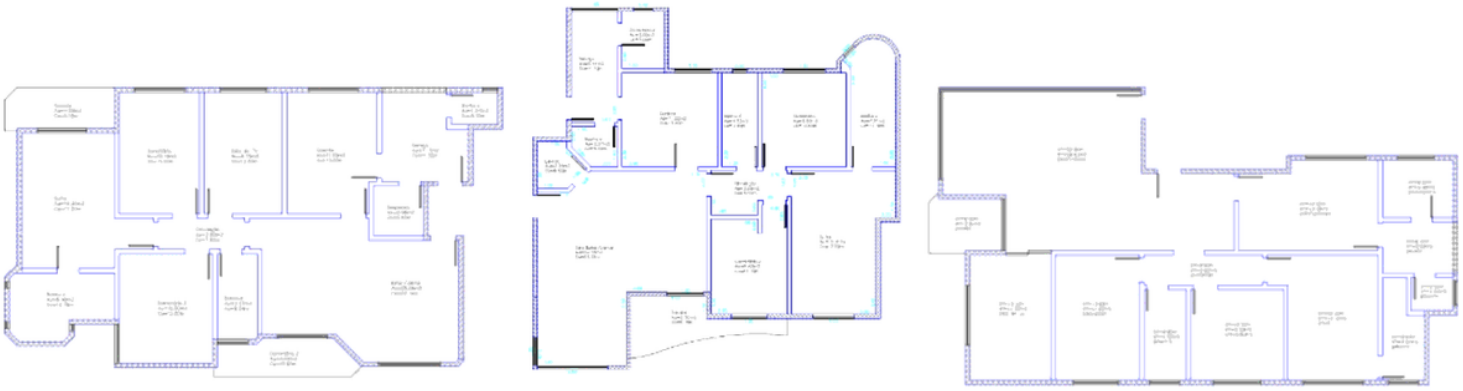

Figure 4

Format of FPL polygons

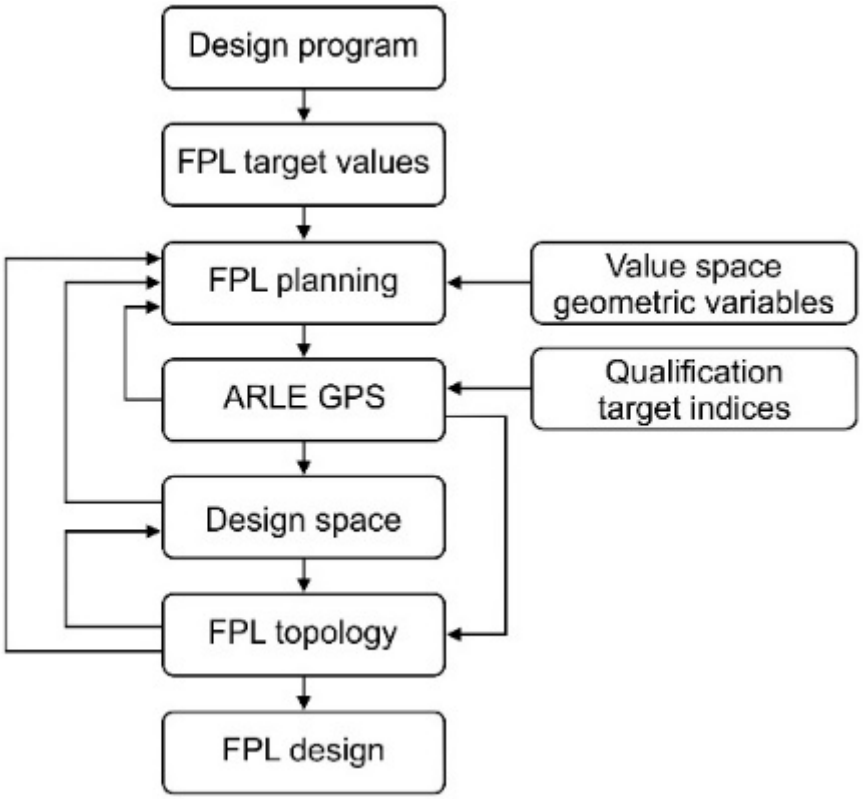

Figure 5

ARLE systematic model of exploration and coevolution - case study approach

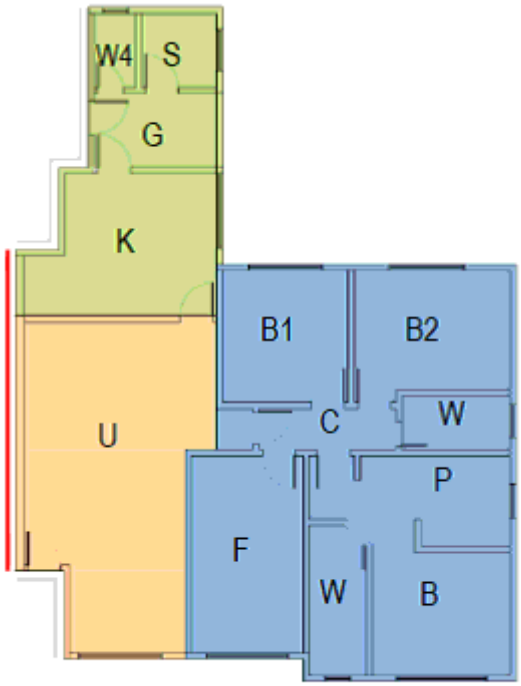

Figure 6

FPL student 018

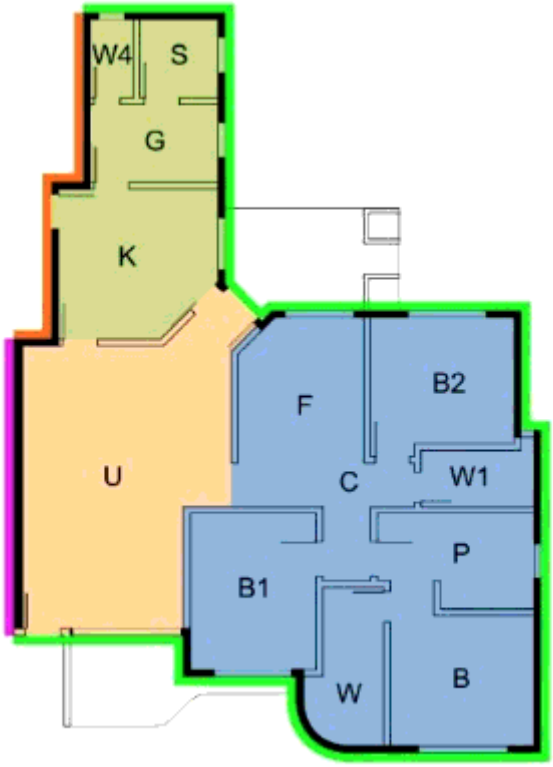

Figure 7

FPL 167

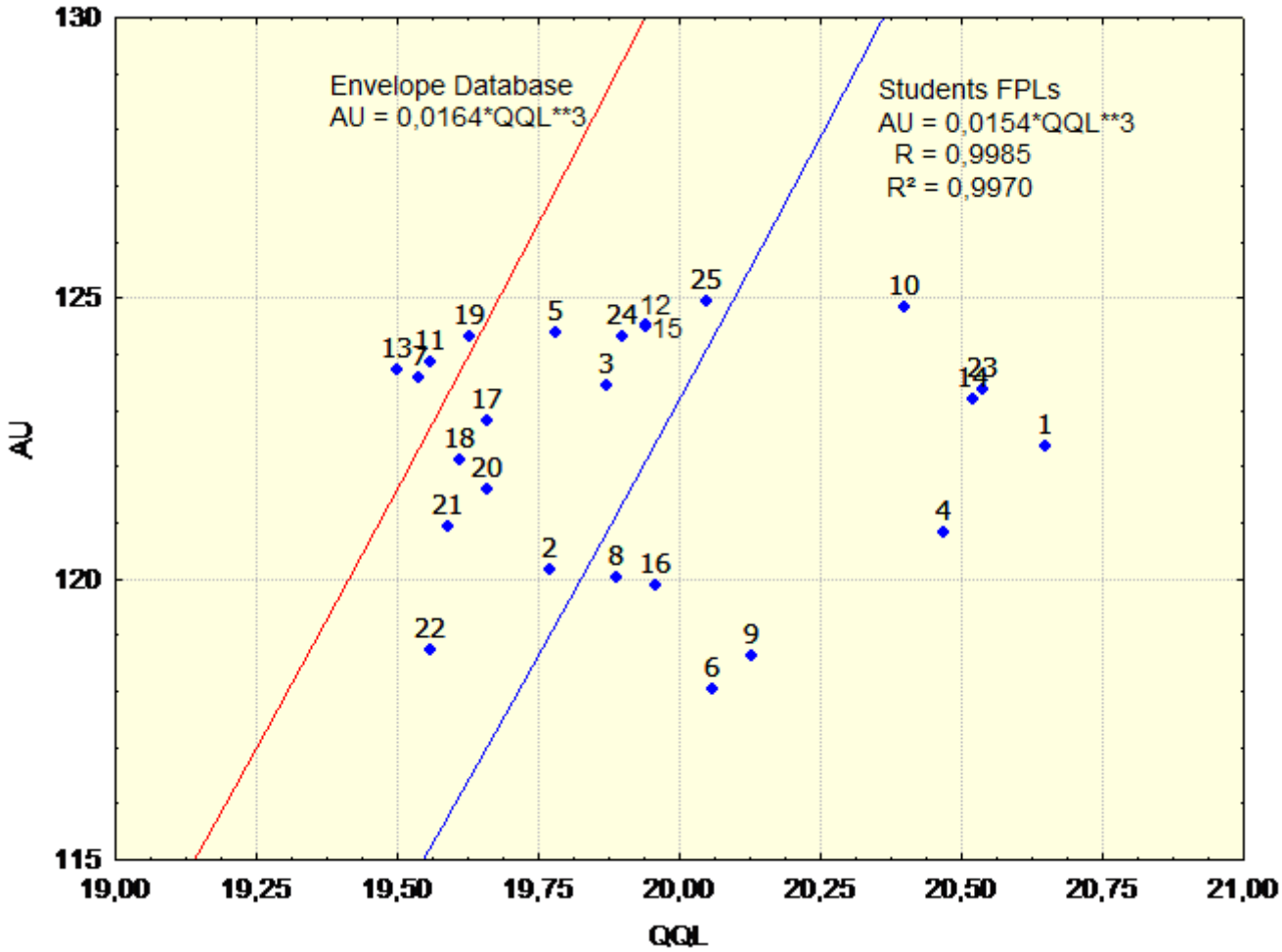

Figure 8

Geometric QQL qualification of the FPLs planned by the students

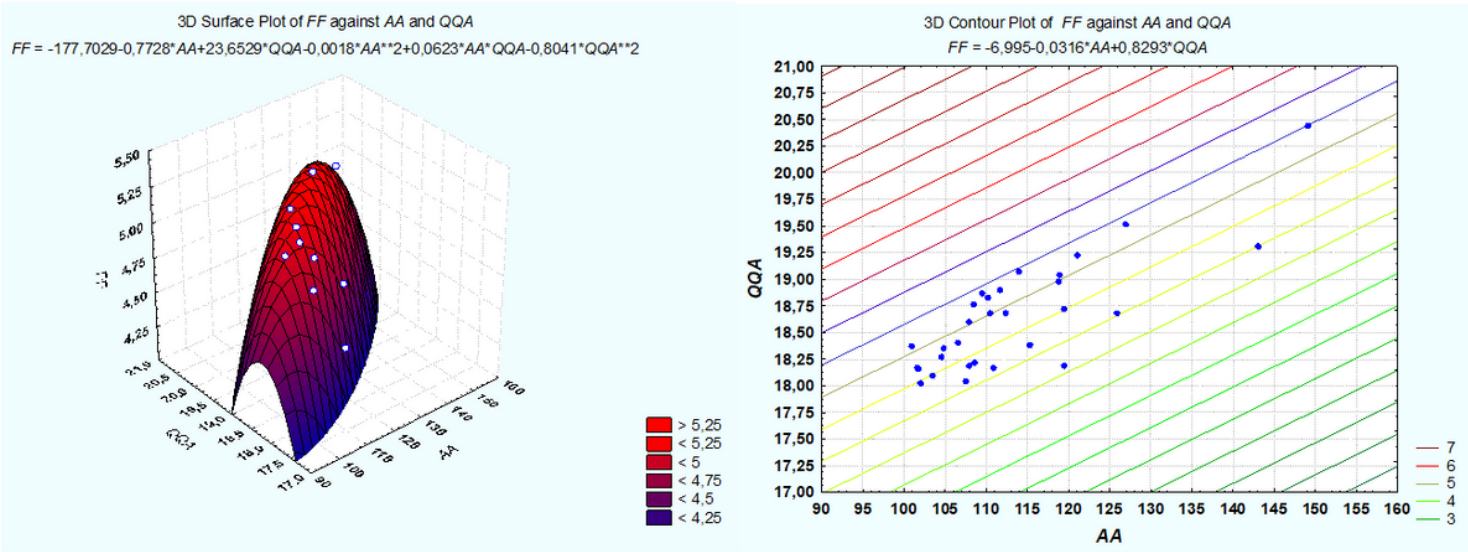

Figure 9

Response surface *FF* against *AA* and *QQA*

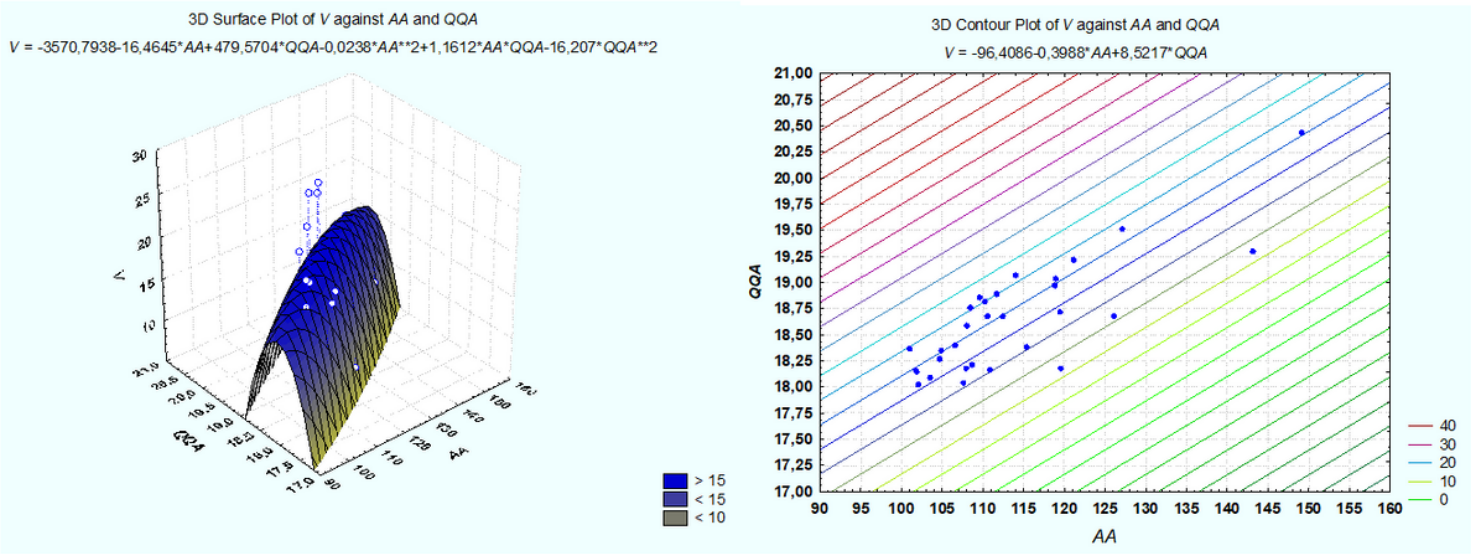

Figure 10

LV response surface against *AA* and *QQA*