Acta Scientiarum

http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v45i1.62821

ARLE GPS: A computational tool to aid architects in spatial planning of house

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ABSTRACT. The floor plan layout (FPL) is conceptualized as an ill-defined problem, due to the identification and formulation of objectives not being fully clear in the conceptual phase of the design. A solution to this issue is to convert the ill-defined problem into a well-defined problem. That is, to make the problem explicit, already in the initial phase of the design process, so that it readily allows the architects to know the requirements and constraints, to formulate the goals, and to apply solution strategies they can manage while solving the problem. This conversion makes it possible to solve the problem by a scientific method, through mathematical modeling of the decision-making problem, rather than by a drawn method, via sketches. It allows the architect to establish a relationship between design variables and house performance attributes, and to know the limits within which the solution, or solutions, can be found, aiding him in generating optimized solutions. In order to contribute to the solution of this issue, we present the computational tool ARLE GPS (geometric planning solver). The tool acts as a physical-biological model of the FPL of house. The physical model is structured by a sophisticated mathematical model, which provides a set of metrics for objective (mathematical) analysis and evaluation, simulation, optimization, rating, and solution selection. The biological model collects, stores, transcribes, and retrieves genetic information from the FPL. The functionality of the physical-biological model allows to construct and explore physical-biological design spaces of FPL, and to establish their value spaces. Its operationalization occurred as an innovative acting tool in the housing architecture design education system.

Keywords: house design; spatial planning; floor plan layout; simulation; evaluation; optimization; cost.

Received on March 7, 2022.
Accepted on October 14, 2022.

Introduction

The floor plan layout (FPL-floor plan layout) represents a system that performs a function or process that results in the output defined by the spatial configuration, or spatial planning of the FPL, which is conceptualized as an ill-defined, complex, challenging, and wicked problem (Simon, 1973; Papalambros & Wild, 2000; Helme, Derix, & Bagot, 2014; Bahrehmand, Batard, Marques, Evans, & Blat, 2017). In an ill-defined problem, requirements, and constraints as well as the identification and formulation of the goals are not entirely clear, particularly in the conceptual design phase (Eastman, 1969; Simon, 1973; Roberts, Archer, & Baynes, 1992; Michalek & Papalambros, 2010). This lack of clarity/explicitness of the problem induces a wide range of solution possibilities, uncertainties in the strategies to address the problem, which results in different implications and difficulties to solve the problem (Wortmann, Costa, & Nannicini, 2015), such as:

i) meet the multiplicity of goals, requirements, constraints, viewpoints, and tastes; arising from the "inherent complexity" of design junctures, which is usually acquired through extensive design practice (Sönmez, 2018);

ii) quantify the quality of the solution, due to the discontinuous and multimodal design space, which implies a vast number of alternatives, which cannot be explored manually (Dino, 2016);

iii) refine the solutions without compromising problem objectives (Bao, Yan, Mitra, & Wonka, 2013);

iv) finding the best solution(s) to the problem, due to the lack of a clear definition of what it is, and how to achieve the optimization (Weise, Zapf, Chiong, & Nebro, 2009).

And with the aggravating factor in most cases, it is not possible to objectively evaluate whether the developed solution is successful (Archer, Baynes, & Roberts, 2005). Research on the design process is closely linked to the investigation of human ability, of how architects design. In turn, understanding the design process, lies in understanding the architect's role in relation to design strategies and solution skills. It is a major area of methodological research, with respect to the study of design processes, and in development and application of techniques to aid in the process (Cross, 2001). In this process, according to the conventional FPL solution approach, the architect analyzes the problem, internalizes the design constraints and goals, and uses their skill and experience to establish a problem-solving procedure (Nagy et al., 2017). This procedure, however, is conceptualized as ill structured, due to the issues above, and the process cycle, which favors the initial solution proposal (or at most the generation of a handful of similar solutions), which is continuously refined (Hofmann & Rinke, 2018), on the simultaneous (strategic) development of different proposals solutions (Dino, 2016). It can be said that design problem solving is not simply the question of how to find a solution to a given problem, it is above all, how to plan the solution that meets the needs or wants, which motivated its initial description. The most important aspect of the design process is the conversion, transformation, or description of the initial requirement into a well-defined problem whose solution, or distinct solutions, meets the original needs or desires. The art of the designer is more in the construction of problems than in their solution (Smithers, 1992). An appropriate alternative to solve this issue is represented by the design problem-solving process as a rational process. In this case, the problem should be clear, such that the architect can apply strategies they can manage while solving it. Analyzing design as a rational problem-solving process implies walking in the logical-positivist framework of science, appropriating the "classical sciences," such as physics, as a model for a science of design (Kees & Dijkhuis, 1995). Structuring a problem in a rational, i.e., well-defined way, enables its resolution to be executed by a scientific method, through mathematical modeling of the decision-making problem, rather than a draw method, via sketches (Papalambros & Wilde, 2000; Archer et al., 2005). A key aspect of the mathematical modeling approach using formal quantitative and qualitative methods, geometric configurations, and conceptual requirements, is that it creates a link between the structural form of a design, and the different functional capabilities it makes available (Peponis, Wineman, Rashid, Hong Kim, & Bafna, 1997). This approach can establish a relationship between design variables and performance attributes (Mahdavi & Gurtekin, 2001) as well as reveal the limits within which the solution or solutions can be found and generate the best solutions (Davis & Gristwood, 2018). This approach corresponds to a view of design as research (Kannengiesser & Gero, 2018).

Material and methods

The establishment of an analogy model demarcates the initial action of the construction of the ARLE GPS computational tool. The model is defined by collecting, quantifying, and qualifying the geometric planning variables of the FPL, analogously with the functional and usability performance of the house, here represented by a verticalized house, i.e., an apartment. These variables shape the horizontal plane, quantify, and qualify its spaciousness and configuration, which represent the two main geometric conversions of the FPL solution (Hillier, 1998). The capture, quantification and qualification of the configuration and spaciousness of FPLs is achieved through the relationship between the vertical and horizontal planes. Defined by the quantification and qualification of the variables: useful surface area (*AU*), and perimeters internal (*PU*) and external (*PE*). On the other hand, the internal perimeter, when allocated to confined functional spaces (*PR*), or circulation (*PC*), is defined as a non-qualifier. The surface area has the function of providing the horizontal plane used for dimensional modeling of the rooms of house (Medjdoub & Yannou, 2000). It establishes the spaciousness of house, which defines an indicative and overriding attribute of its performance. Its participation in the qualification of the FPL is computed by the spaciousness index (*IA*). The internal perimeters act on the performance of the house by establishing the function of a generator system of the vertical planes of the house. 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 & 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. Confinement is related to the problem of not allowing users to have direct access to sunlight, in addition to making it difficult to exchange air and heat with the external environment, and not least, making it impossible for users to access the landscapes of the outside world. Its contribution to the house performance 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 passageway and connection, which configures a locomotion room (Bahrehmand et al., 2017). Its contribution to the house performance is established by the circulation index (*IC*). The external perimeter has the function of establishing the house armoring in relation to external protection, climatic safety, and to provide 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 & Yannou, 2000). Their participation in the qualification of the FPL is computed by the exteriorization index (IE). The condominium and symmetry perimeters define the section of the house 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 is shared with the collective area of the building, and the symmetry perimeter 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. However, they are contributors to the cost of converting the FPL into the house artifact and are computed for this purpose. Geometric variables quantified and qualified in the house performance analogy model represent the totality of variables used for geometric FPL planning, and structure the LEQC meta-model.

Method

Solution model of the FPL as a well-structured problem by ARLE GPS

The conceptual boundary between well-structured and ill-structured problems is vague, bland, and not subject to formalization. However, an ill-structured problem can be notably characterized as an abstraction, in terms of what they are not. Under these conditions, requirements proposed by Simon (1973), which a problem must met in order to be considered well structured, are:

i) ensure the establishment of criteria that allow the evaluation of the proposed solutions, in a continuous way;

ii) certify the problems states, initial, intermediate and target;

iii) allow adjustment and rearrangement of the possible solutions to reach the solution (target) state;

iv) share and reproduce the solutions reached with/in other problem spaces;

v) structure a solution model that reproduces a law of relationship between state changes in the solution.

A problem formulated in such a way that it meets these requirements can be, according to Simon (1973), solved by a serial machine called “robots,” and named a “general problem solver” (GPS), which nowadays can be represented by a software. Under these conditions, the solution of the problem with the help of the GPS is established so that it meets the:

i) characterize and define the initial, intermediate, and target states;

ii) describe the state of the solution, and test the solutions to check whether the desired state was reached;

iii) establish a set of operators to promote the change of states, along with the conditions of applicability of these operators;

iv) define a set of differences or tests to detect the presence of these differences between pairs of states;

v) indicate the existing connections, associating with each difference, the relevant operators to reduce or remove the differences.

Thus, the principles and systematic approach of the GPS serial machine establishes its operation in solving formally defined problems (Simon, 1973; Simon, 1996). This proposal presents affinities with the systematic model developed by Archer (1968), who defines a relationship between an objective or goal to be achieved in a design, which he calls quality, and the action directed by variables promoting the actions to achieve this objective. The information and instructions proposed by Archer define the basic structuring and functionality of the LEQC meta-model, regarding:

i) expressing the value of the design solution qualification, and defining the target value of this qualification as a criterion or threshold for acceptability of the solution;

ii) defining the input/output (*I/O*) mechanism of the qualification model through an appropriate metric to capture, quantify, and qualify the variables promoting the qualification action;

iii) constructing a model that represents the law of relationship between the qualification objective and the action directed by the variables to promote this qualification;

iv) establishing solution simulation, as an analogy of the qualification of the design solution in relation to the performance of the house artifact;

v) solving the issue of judging a solution by establishing objective (mathematical) criteria, since, when performed subjectively, the judgment may be altered, or diverge with the change of arbitrator;

vi) maximizing the added value of the artifact, and choose cost as the arbitrator of the selection of optimal solutions (cost/quality);

vii) collecting, tabulating, sorting, and storing solution data;

viii) developing an effective model for establishing analogies and simulations, capable of referencing a logical structure of the problem, and competent to generate solutions to the problem;

ix) valuing the creative role of the architect as a pilot in the process of conceiving ideas and establishing the principles of the design solution.

Likewise, Archer's systematic model, states that the act of designing requires:

x) being in accordance with the objectives of the problem;

xii) identifying the qualities or structural conditions that must be present in the result;

xiii) defining the relationships between quality (performance) variables and goal achievement variables;

xiv) establishing the limit and ideal states for the qualities;

xv) identify the decision variables available to the architect and their correlations;

xvi) formulating a decision-making model that meets the objectives of the problem;

xvii) ensuring that the interdependence of the qualities constitutes an executable and acceptable domain;

xviii) establishing that one or more quality states are in this domain;

xix) selecting an optimal proposal.

Therefore, a successful/structured design solution, according to Archer and Simon, should be grounded in establishing a proper scope of the "problem" through a focused or targeted approach to collect and gather data and information of the problem, prioritizing the demarcation of concepts and criteria for the solution of the problem (Cross, 2018). However, the adoption of a physical model of design research was, according to Langrish (2016), one of the determining factors in the rejection of the design rational methods developed in the 1960's, considered the first generation.

Briefly, on account of the following issues:

i) perversity of the real-world problems;

ii) inability of physics to deal with the complexity of design;

iii) demand for a biological approach in the design process of artifacts of the artificial world. Aiming to use the information of inheritance and genetic transmission of existing artifacts, for the creation of new artifacts (Bayazit, 2004; Langrish, 2016).

Furthermore, Davis and Gristwood, (2018) point out the existence of a still persistent tension between design theory and practice, due to the existence of disruptions in the model proposed by Archer, motivated by:

i) complexity arising from the interrelationship of the design variables;

ii) possibility of design program review;

iii) assurance of good data/information.

The first generation of Design Research began in the 1960's and sought the systematic and rational establishment of problem solving (Atkinson & Oppenheimer, 2016). These methods, thus established, sought rational decision-making procedures, incorporation of heuristic rules and techniques, and application of scientific knowledge in the design process, sought to elaborate rational decision-making criteria and optimize them, a condition considered at the time of their formulation, and still today, difficult to achieve (Cross, 1993; Bayazit, 2004) and not directly achieved by the conceptual models proposed. In order to contribute to the conversion and solution of FPL problem of a house, as a rational process, the conceptual models of Archer and Simon are converted into the mathematical metamodel LEQC, which is transcribed in the computational tool ARLE GPS. The ARLE GPS tool is structured by joining the systematic model "field of action" of the design resources proposed by Archer, with the GPS "general problem solver" model proposed by Simon. From this union is born the LEQC meta-model that establishes the "rational action-decision field" of design resources. The ARLE GPS tool defines a structured strategy for solving the problem of geometric planning of the house (FPL) by applying the GPS proposed by Simon, converted to solve the geometric planning of the house (GPS - geometric planning solver). Since, the combination/fusion of Archer's and Simon's models allows to convert the conceptualized ill-structured design problem into a well-structured problem, and thus to solve it through mathematical modeling of the systematic and rational decision-making problem. This planning acts similarly to the construction of a geometric prototype FPL of the house; it gathers guidelines and instructions for assembly, modeling, and refinement of design. ARLE GPS assembles this prototype, builds the geometry of the FPL, and through this prototype, using the biological model, builds a solution to the topological issue. It enables the architect to start the process of modeling the topological solution using the representative components of the rooms, already dimensioned, evaluated, and optimized with respect to the required performance, and knowing the order of assembly and connectivity of the components in the structure/house, as well as a description of the shape of the FPL polygon. On the other hand, issues reported by Langrish, and the problems mentioned by Davis & Gristwood, determinants of the rejection of the first-generation physical models, are fully solved by the LEQC meta-model, through its physical-biological model. The physical model is structured by a sophisticated mathematical model, which provides a set of metrics for objective (mathematical) analysis and evaluation, simulation, optimization, classification, and selection of optimal solutions. The biological model collects, stores, transcribes, and retrieves genetic information from the FPL. The functionality of the physical-biological model allows to construct and explore the physical-biological space of the FPL, and to establish its value space. Thus, the structure, functionality, and robustness of the LEQC meta-model converted into the ARLE GPS computational tool makes available an alternative for dealing with the complex problem of the FPL (Gero, 1998; Langrish, 2016).

LEQC meta-model

The starting point for the structuring of the LEQC metamodel, and consequently of the ARLE GPS tool, is established by an analogy model. This model operates as a collector and transferor of house performance information, for the geometric planning of the FPL (Gane & Haymaker, 2012). The mathematical model of analogy is defined under the proposal of a power regression curve, according to the model proposed by Kirkpatrick (1970), shown in Figure 1.

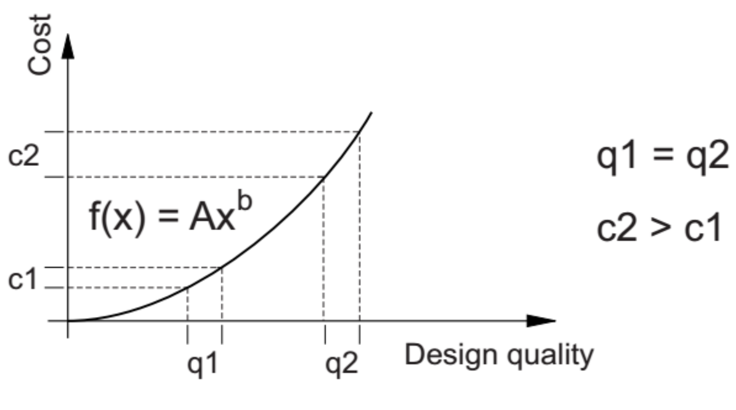

Figure 1. Model of design quality versus cost. Source: Kirkpatrick (1970).

It is established by a cubic power curve, y= Ax^3, and defines a law of analogy that relates the physical functional performance of the house, with the geometric qualification of the FPL, shown in Figure 2.

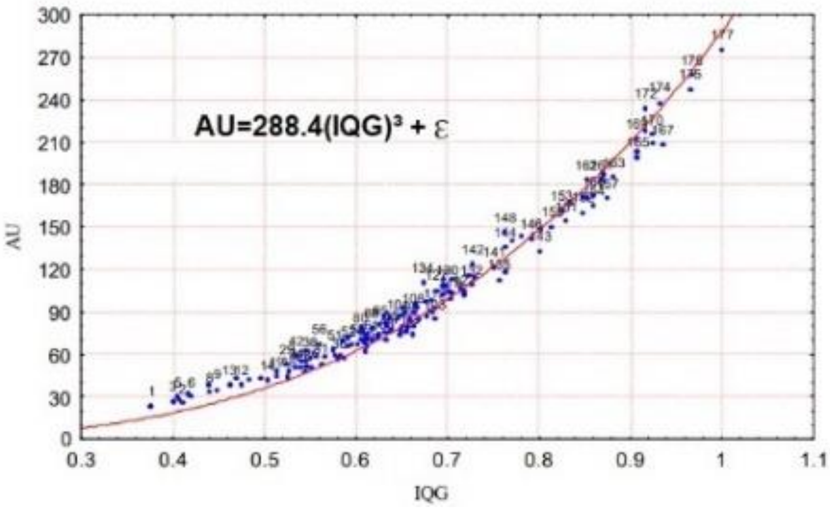

Figure 2. Regression Model. Cost x Quality. Source: The author's.

The mathematical model, in turn, is commuted into the substitute model or LEQC meta-model to simulate the performance of the house, which is established by the geometric qualification of the FPL. The certification of the mathematical law of analogy regarding the consistency and robustness of the LEQC meta-model can be measured by statistical processing of the design space established by 180 FPLs of apartments with three family bedrooms. The result of this processing is presented in Figure 3 and shows the behavior of the house performance.

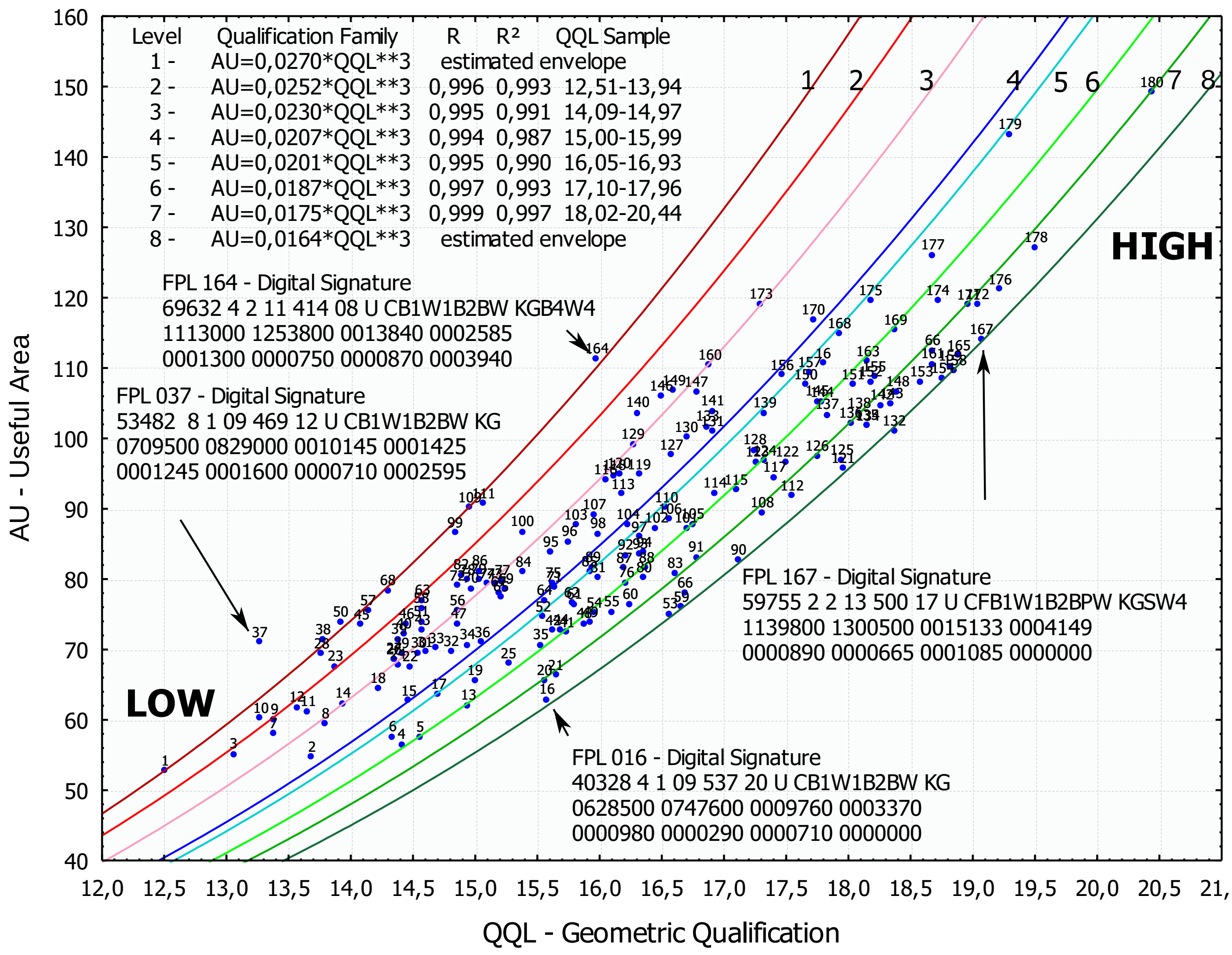

Figure 3. Geometric qualification of FPLs in the design space.

ARLE GPS physical model

The FPL consists of a graphic representation in the 2D plane, configured by the geometric variables area and perimeter, which describes the polygons representing the rooms of the house. The physical model is structured through these variables (Franz, Von der Heyde, & Bulthoff, 2005) to capture, quantify, and qualify the architectural spaces of the house, through the size, position, and the contribution of geometric variables of the FPL, capable of validating the performance of the house, employing the "$perimeter/\sqrt{area}$" ratio; (D'Amico & Pomponi, 2019). The relationship that captures spaciousness (*IS*) is established through the horizontal plane quantification index; which defines the dimensionless value of the polygon spaciousness, considering its surface area (*AF*).

$$\mathrm{IS} = \mathrm{AF}/\mathrm{m}\sqrt{\mathrm{AF}} \quad (1)$$

where: 1/m - unit dimensional factor (m is the unit of measurement meter, when the surface area is calculated in square meters). The physical interpretation of the index is that it represents the number of "*IS*" times the length of the unit area strip (height = 1.0 m), equal to the side of the square polygon of area equal to *AF*. The relation that captures the configuration (*IG*) establishes a dimensional quantifier of the vertical plane, which defines the adimensional value of the polygon configuration, considering its perimeter (*PF*).

$$\mathrm{IG} = \mathrm{PF}/\sqrt{\mathrm{AF}} \quad (2)$$

The physical interpretation of this index is that it represents the number of "IG" times the length of side of the square polygon of area equal to *AF*. The quantification of the amplitude of the FPL (AI) is calculated by adding the useful area of the polygons representative of the rooms that make up the functional spaces of the house (*AU* - useful area of the FPL).

$$\mathrm{IA} = \sqrt{\mathrm{AU}} \quad (3)$$

The FPL configuration is defined by the indices: internal configuration (*IP*), exteriorization (*IE*), circulation (*IC*) and confinement (*IR*). With the introduction of the wall variable (equivalent to two perimeters), the qualification indices are quantified by equations 4 - 7. The calculation of the shape factor (*FF*) is defined by Equation 8 and represents a quantification and qualification index of the shape of the FPL polygon, comparatively to the square polygon, whose value is equal to four.

$$\mathrm{IP} = \mathrm{PU}/(2 * \sqrt{\mathrm{AU}}) \quad (4)$$

$$\mathrm{IE} = \mathrm{PE}/(2 * \sqrt{\mathrm{AU}}) \quad (5)$$

$$\mathrm{IC} = \mathrm{PC}/(2 * \sqrt{\mathrm{AU}}) \quad (6)$$

$$\mathrm{IR} = \mathrm{PR}/(2 * \sqrt{\mathrm{AU}}) \quad (7)$$

$$\mathrm{FF} = (\mathrm{PE} + \mathrm{PX} + \mathrm{PY})/\sqrt{\mathrm{AT}} \quad (8)$$

where: *PU* - sum of internal perimeters of the rooms of the house; *PE* - external perimeter of the house; *PC* - sum of perimeters of the circulation rooms; *PR* - sum of perimeters of the confined rooms; *PX* - condominium perimeter; *PY* - symmetry perimeter; *AT* - total area of the FPL.
The sum of the horizontal and vertical plane qualification indices, according to the LEQC meta-model, determines the geometric qualification (*QQL*) of the FPL.

$$\mathrm{QQL} = (\mathrm{IA} + \mathrm{IP} + \mathrm{IE}) - (\mathrm{IC} + \mathrm{IR}) \quad (9)$$

According to Archer (1968), in order to evaluate the qualification of a design, it is possible and recommended to use another design that defines the required quality, as a reference. This reference enables its use as an indicator of performance and optimization of the solution (Choudhary & Michalek, 2005). The concept of the benchmark design and the target value of the required quality represent one of the foundations of structuring the LEQC meta-model. It evaluates a solution of the FPL against a target value belonging to a region of the design value space, i.e., the required quality *QQA* (target), or *QQA* defined by any other FPL, established as a benchmark for evaluate and optimize the candidate solution. The evaluation is always processed in comparison with the required quality. The FPL geometric quality index (*IQG*) is defined by the degree to which the geometric qualification (*QQL*) meets the target value (*QQA*), i.e., the required quality.

$$\mathrm{IQG} = \mathrm{QQL}/\mathrm{QQA} \quad (10)$$

Simulations carried out by meta-modeling using the geometric quality index (*IQG*) demonstrate that this index represents a loss model (Martins, 2001); in accordance with the quality approach advocated by Taguchi (Murphy, Tsui, & Allen, 2005). Taguchi establishes the delimitation of several quality levels or regions according to the magnitude of the presence of the qualifying variables in the product (Papalambros & Wild, 2000; Gane & Haymaker, 2012; Sönmez, 2015; Sönmez, 2018). Taguchi emphasizes the need to set a target value for the required quality. According to this approach, losses generated by a product are basically caused by the variability in its intrinsic function and the harmful side effects arising from the use of the product during its lifetime. They must be determined in terms of the cost of losses. The LEQC meta-model determines them through the variables *VAN* (monetary cost of losses), and *IVN* (geometric cost of losses). The comparison of geometric qualifying values of the FPL with a target value, representing the quality, determines that the insufficiency of geometric qualifying variables, compared to the adopted target, represents a loss (*LO*) during the use of the house. On the contrary, when these values exceed the target, a gain occurs. This value is defined by the representative variable of the geometric cost defined by the useful area (*AU*), which is called nominal area (*AN*), obtained through the mathematical regression model presented in item 4.

$$\mathrm{AN} = (\mathrm{AU} \pm \mathrm{LO}) = \mathrm{AA}(\mathrm{IQG})^3 \quad (11)$$

The ratio of the nominal area (*AN*) to the useful area (*AU*) is called the Loss Cost Index (*IVN*). It defines a geometric cost index of the FPL considering losses (or gains). This index defines the inexistence of losses, when the value is equal or higher than 1.0, and its existence when the value is lower than 1.0.

$$\mathrm{IVN} = \mathrm{AN}/\mathrm{AU} \quad (12)$$

The geometric quality cost *VAQ* defines the ratio of geometric cost to geometric quality (*AU*)/(*QQL*), which establishes the geometric optimization of the FPL.

$$\mathrm{VAQ} = \mathrm{AU}/\mathrm{QQL} \quad (13)$$

The equations presented above describe the internal laws of the LEQC meta-model, acting in the action-decision field of geometric variables of the FPL, and define geometric cost, geometric qualification, geometric qualification evaluation, and geometric cost/geometric quality ratio.

ARLE GPS biological model

The biological model aims to know, compare, transmit and transcribe genetic information of the FPL individual, as well as to establish a system for ordering and classifying them, aiming at the construction and exploration of design spaces, and the retrieval of information on inheritance and genetic transmission of existing FPLs, for the generation of new FPLs (Markus, 1993; Jo & Gero, 1998; Langrish, 2016). In genetics, the information of an individual's structure is stored in a sequence of genes, which defines its genetic code. Genetics identifies genes, their clusters, and their sequence structure in species genomes, which is the genetic material used to represent the organism at its reproductive level (Gero & Kazakov, 1997; Langton, 2000; Steadman, 2008). Similarly, the genetic code of the FPL informs: performance, formation, functionality, zoning, order of rooms assembly, connection between rooms, and quantifies the geometric assembly variables of the FPL of a house. It uses for this purpose the genes *Gperforme* (performance), *Gform* (form), *Gfunction* (function), *Gtopology* (topology), and *Gspace* (dimension). The first number of the FPL genetic code (five digits) is established by the gene that defines the geometric cost of geometric qualification of the FPL in the unit of square centimeters (performance). The *Gform* gene provides the variables for forming the house structure: the first digit sets the reproduction number of the structure in the plane (*Nf*); the second digit demarcates the number of connections to the external environment (*Ne*); the third and fourth digits set the number of functional rooms of house; the next three digits define the shape of a house, *FF* x 100 (form factor multiplied by one hundred - sequencing set by integer number); and the last two digits inform the number of vertices/sides (VL) of a house modeling FPL polygon. The *Gfunction* gene defines the design program and reports: function of the rooms in a house and the functional zoning of the rooms (social, intimate, kitchen and service). The *Gtopology* gene defines the order of assembly of the rooms, and their connections. The

Gspace gene quantifies the geometric variables that define the structure of house: AU – useful area, AT - total area, PU - internal perimeter, PE - external perimeter, PX - condominium perimeter, PY - symmetry perimeter, PC - circulation perimeter, and PR - confined perimeter (dimensions are computed in centimeters). The informations transmitted by the *Gspace* gene makes it possible to directly determine/retrieve from the gene, the geometric qualification index (QQL) of the FPL, which by analogy indicates the performance of the house.

ARLE GPS monetary cost model

The geometric qualification of the FPL is an important variable, for the evaluation, optimization, and definition of its positioning in a value space of the design solution. However, this index must be confronted with another equally important variable: the monetary cost of obtaining this quality. By comparing these two values, it is possible to answer the crucial question of how to maximize the quality and minimize the monetary cost of obtaining it. Without this, cost determination and analysis will be a tool only for cost knowledge (Markus, 1971) and not for the optimization of the design solution. A differential of the ARLE GPS tool and great advantage of its use is that the monetary cost of the solution of the FPL is calculated using the same geometric variables of its geometric structuring that are used to determine its geometric qualification. The tool thus allows the architect to simultaneously evaluate the influence of monetary cost of the geometric solution of the FPL, evaluate and select the best solution of the FPL (strategic development/optimization), defined by the lowest monetary cost to meet the required quality. The cost of the horizontal plane is defined by the cost of finishings the floor and the surface area of the ceiling of the house, considering its position in dry rooms *VAd* (living, bedroom), or wet rooms *VAw* (bathroom, kitchen, service). The cost of vertical planes is defined by the construction cost of the internal and external walls, cut in half lengthwise, resulting in two halves, three perimeters: *VPd* (dry), *VPw* (wet), and *VPE* (external); considering their respective finishing, components and connections, and their height equal to the distance from floor to ceiling. In this model, the structural existence of horizontal planes (floor and ceiling slabs), and vertical support (columns) are considered. The cost determined by the proposed model is called monetary cost. The other variables that determine the cost of converting the FPL into a house, such as foundation, structure (columns, beams, and slabs), roofing, electrical and hydraulics systems, and other costs, are considered semi-independent in the LEQC meta-model. The cost of converting the FPL into a house artifact, via the monetary cost (*TVL*), is computed by equation 14.

$$\mathrm{TVL} = [\mathrm{Ad} * \mathrm{VAd} + \mathrm{Aw} * \mathrm{VAw} + (\mathrm{Pd} + \mathrm{PX}) * \mathrm{VPd} + \mathrm{Pw} * \mathrm{VPw} + \mathrm{PE} * \mathrm{VPE}] \quad (14)$$

where: *Ad*= sum of dry area; *Aw*= sum of wet area; *Pd*= sum of dry perimeter; *Pw*= sum of wet perimeter; *PE*= external perimeter.

The monetary cost *VGL*, per unit useful area *AU*, is defined by equation 15.

$$\mathrm{VGL} = \mathrm{TVL}/\mathrm{AU} \quad (15)$$

The monetary cost of geometric qualification *VQL* is equal to the monetary cost of conversion FPL, per unit of geometric quality.

$$\mathrm{VQL} = \mathrm{TVL}/\mathrm{QQL} \quad (16)$$

The monetary cost *VAN* (losses or gains) is equal to the unit monetary cost *VGL* per unit of nominal floor area *AN*.

$$\mathrm{VAN} = \mathrm{VGL}/\mathrm{AN} \quad (17)$$

Equations 14 to 17 define the internal laws of the LEQC meta-model, acting in the action-decision field of the monetary costs of FPL/house conversion.

Standard Finishes of the FPL/house conversion

With the definition of a standard of finishes, the cost of converting the FPL into a house artifact is established, according to the quantification of geometric variables. Costs are determined separately according to the geometric variables that define its monetary cost (*VPE*, *VPw*, *VPd*, *VAd*, *VAw*); by computing the cost of materials, components, and services used in its construction, as shown in Table 1. Once the conversion costs of the FPL geometric variables are established according to the finishes adopted, they define the reference values of the conversion cost of all other developed or explored FPLs, considering their similarities (distance from floor to ceiling), and the same standard of finishes.

Conversion costs FPL/house

The monetary cost of 200 FPLs of an apartment design space with the configuration of three bedrooms is determined here considering two appropriations: monetary (*VGL*), by means of the monetary cost of geometric variables of structuring the FPL; and quantitative (*VVL*), by quantitative appropriation and cost of the materials, components and services, used to convert FPL into a house, in the traditional way of cost determination, in both cases, excluding the costs of the variables considered semi-independent. The comparison between the two cost determination models *VGL* and *VVL*, through the cost ratio ($RC = VGL/VVL$), shows that the results obtained are practically equal, and do not present significant standard deviation values, proving the consistency and robustness of the monetary cost model. The cost of the materials, components, and services used in these conversions (FPL/house) are made from existing cost tables in the construction area, referring to the month of February 2010 (Pini, 2010), which are listed in Table 1.

Table 1. Monetary cost of converting the FPL in a house artifact.

Geometric variables/elements	Cost values (U$ dollars)
VAd=cost of the dry horizontal plane (useful area of the FPL dry floor)	127.31
VAw= cost of the wet horizontal plane (useful area of the FPL wet floor	125.08 ±2.22
VPd=cost of the dry internal vertical plane (dry internal perimeter of the FPL)	105.60±1.42
VPw= cost of the wet internal vertical plane (wet internal perimeter of the FPL)	159.70±3.70
VPE= cost of the external vertical plane (external perimeter of the FPL)	328.80±29.58
VGL= monetary cost of the FPL /m^2 of useful area	448.10± 28.96
VGL= min=minimum monetary FPL cost/m^2 of useful area	366.81
VGL= max=maximum monetary FPL cost/m^2 of useful area	524.02
RVG=VGLmax/VGLmin	1,43
RVV=ratio of the monetary cost of the vertical plane to the total monetary cost (VGL) (percentage)	70.79±2.05
RHV=ratio of the monetary cost of the horizontal plane to the total monetary cost (VGL) (percentage)	29.21±2.05
VVL=quantitative cost of the FPL/ m^2 of useful area	449.67±28.58
VVL=min minimum quantitative FPL cost/m^2 of useful area	369.92
VVL=max maximum quantitative FPL cost/m^2 of useful area	544.92
RVV=VVL max/VVL min	1,47
RC=monetary cost (VGL) /quantitative cost (VVL)	1.002±0.018

Results and discussion

Planning, evaluation, and generation of FPL

An example of the application of the ARLE GPS computational tool by a student to solve the spatial planning of the FPL is presented in Figures 4 and 5. The solution obtained meets a range of requirements established for the definition and solution of a well-defined problem, instituted by apartment functionality program, useful area (*AU*) equal to 120 ± 5 m^2; two units per floor; two connection with the external environment; required target performance of the house *QQA*=19.50 in relation to the target area AA=125m^2. This performance, established through the equation *AU*=0.0164**QQL*^3=(19.68), represents the family of FPLs situated at the limit of the high-performance region of the explored design space, as illustrated in Figure 3 (Martins, 2022). Topological data for the assembly of the structure, modeling, and refinement of the design (FPL), such as the assembly order and connections between the rooms of the house, are made available directly by the biological model ARLEGPS, through the spreadsheet shown in Figure 4.

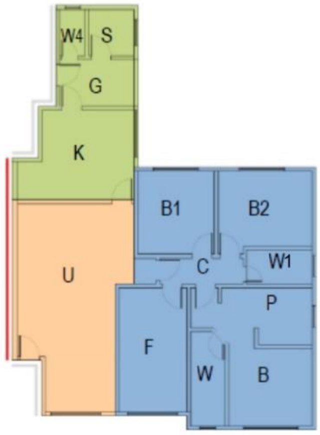

Figure 4. Student-generated design.

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 25,7 %	E1	entrance 1											
		U	living & dining			31,40	25,42				x		x	
		L	living											
		D	dining											
		O	home office											
		H	home theater											
		T	toilet											
	Intimate zone 54,3 %	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	
		P	closet			6,28	10,93				x		x	
		W	master bath			4,97	9,78					x		x
	Service zone 20,0 %	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											
		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

Figure 5. ARLE GPS – Geometric Planning Solver.

Conclusion

The spatial planning and design of the FPL using the ARLE-GPS tool represents a good model for the architect's action in the design process, as well as very much aid the student who is just beginning their contact with the complex world of design, and who does not yet possess the expertise of an architect. The tool fills an existing gap in the field of housing design, acting in an accessible and friendly manner as an aide integrated into the student's or architect's design behavior, to aid them in making rational decisions in the initial phase of design, consequently in conversion of the spatial planning problem of the FPL, conceptualized as ill-defined, into a well-defined problem. In this way, it enables the problem to be solved through mathematical modeling. This modeling relieves the architect or student from repetitive, tedious, and error-prone tasks, and helps them perform simulations and simultaneous evaluations of candidate solutions, repetitiously, in real time, and refine the result of the exploration of the solution space, progressively until the desired optimization is achieved; thus, constituting a strategic process of face and solving the candidate problem. In addition, ARLE GPS enables decision makers: determine the geometric cost, and the monetary cost of converting the FPL into a house artifact; calculate the losses arising from the use of a house as a function of the magnitude of the presence of the qualifying variables in the FPL; reveal the cost of design decisions; build design spaces, establish value spaces, and navigate the design space through the genetic code of the FPL. The model for determining monetary cost through geometric variables that structure the FPL represents a new and powerful tool for decision making. This range of action and support of the tool, provides the decision-taker with facilities and speed to successfully solve the candidate problem; as well as to replicate existing successes, recovering the most appropriate experience instead of repeating the process of generating a solution from scratch; thus, minimizing the occurrence of failures, and optimizing the use of human and computational resources. The spatial planning solution represents one of the determining factors of the variation of the VGL monetary cost of converting FPL into a house; which was higher than 40 percent in relation to the analyzed values of 200 FPLs in the evaluated design space, as shown by the values in Table 1. Cost determination establishes a crucial variable, for optimization of the FPL solution in the design process. ARLE GPS solves this issue by calculating and revealing the cost of the solution, already at an early stage of the design process, from the geometric planning of the FPL, and thus defines a strategic advantage for the decision maker in solving the problem and optimizing the solution. ARLE GPS engages and contributes in this way, aide architects or students in the crucial phase of the house design process, especially in the area of education. The aiding the tool provides to students allows them to establish a level of information, reflective practice, and creativity that accredits them to successfully solve this type of problem in the "life" of the future professional. There are no conflicts of interest to report. "This research has not received any specific grant from funding agencies, in the commercial or non-profit sector."

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