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Exploring the possible role of *parametric design* in addressing the compositional problem: theory and practice of an evolving approach toward the urban design perspective

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Index

Index of figures

Part 0 – Introduction

Few theoretical premises as a starting point for introducing a *parametric urban design* perspective, interpreting the method as a tool for achieving quality arrangements

Part I – The theoretical framework

Reproducing a sound theoretical framework for parametric design: the option of diagramming morphogenetic processes in search of performing outcomes

Part II – Analog and digital parametrics

From *analog form-finding* experiences to the *digital* complexification of modeling: the evolution of constraint systems toward generalized parametric options

Index of tables

Part II – Analog and digital parametrics

From *analog form-finding* experiences to the *digital* complexification of modeling: the evolution of constraint systems toward generalized parametric options

Part III – Case studies and matter for reflection

Interpreting practical experiences as attempts to address the "*compositional problem*": predisposing occupation of shapes and densities parametrically to solar energy gain

Index of graphs

Part 0 – Introduction

Few theoretical premises as a starting point for introducing a *parametric urban design* perspective, interpreting the method as a tool for achieving quality arrangements

Interpreting practical experiences as attempts to address the "*compositional problem*": predisposing occupation of shapes and densities parametrically to solar energy gain

Index of attachments

Abstract

The thesis explores *parametric design* technology from an urban design perspective of development. Precisely, our concern is embracing a genuine orientation to what parametrics could do for the substantive performance of morphology, shifting the focus from a seemingly fashionable, but sterile conception of appearance. Within this framework, we consider a possible finalization of technique based on informing the occupation of available space. The attempt, in this case, is addressing the compositional problem from the standpoint of urban geometry and energy efficiency, which is a humble, but conscious reduction of complexity. Starting from the assembly of generative rules, parametrics may assist designers in returning a blending range of correlations between shape and density options, with direct feedback on consequences that outcome occupation may yield for solar access. The recognition of urban space as a field of complex equilibria, where different demands of occupation intersect likewise different solid-void structures, helped interpret methodology from a critical stance. Though grounded on a non-exhaustive selection of studies and a partial, rudimental experiment, the interface between theory and practice led us to gain awareness of potentials, frictions and development lines of a support system that, borrowed from non-urban domains, is called to embed and simulate the complexity of city forms.

Keywords

Complexity, decision support system, digital technology, energy and urban form, energy efficiency, *Grasshopper*, optimization, *parametric design*, urban design, urban quality, urban simulation.

PART 0 INTRODUCTION

Few theoretical premises as a starting point for introducing a *parametric urban design* perspective, interpreting the method as a tool for achieving quality arrangements

0.1. An introductive discourse about the overarching intents: from a theoretical overview of *parametric* design to the appraisal of limits and prospects for *urban* design

0.1.1. The "*compositional problem*": the arrangement of *densities* and *shapes* as a determinant matrix of urban effects, calling for assisting urban design tools in hard times

The elaboration of formal solutions to a demand of meaningful urban environments represents one of the key duties nurturing designerly outlooks and reflections. In compliance with an urban design perspective, we could conceptualize the nebula of hardships connected to filtering morphological choices as the "*compositional problem*". This struggle seems to involve designers across different scales of the project, from mechanical engineering and industrial design to operational planning, passing through the architectural dimensions. While sharing some degree of creative thought for the sake of original options, these domains travel along scales at increasing levels of complexity, due to the gradual unclasp of various and concomitant effects. In parallel, we can observe a changing degree of freedom in manipulating, devising and exploring hypotheses, which furtherly stresses the rise of intricate patterns of alternatives as a number of complementary and intersecting restrictions appear at up-scaled developments of morphology.

In particular, the essence of compositional problems for the built environment insists on how both boundaries and elbow rooms for action calibrate a combinatorial system of *densities* and *shapes*, which can be appreciated as a decisive matrix of implications through the innately multidimensional spectrum of an urban setting (Carmona, 2010). In line with this perspective, we call *morphology* a particular way of solidifying an abstract concept of "density" in relation to a concrete materialization of "shape". This *discidium* between abstract and concrete dimensions of the project permeates the backbone of such burden: in fact, density and shape do not fulfill any correlation but the one chosen with discretionary choice over what Lawson (2006) describes as *design synthesis* processes. In other words, designers can achieve one specific density by means of differing shapes, each having differing incremental impacts on density attributes (*figs.* 1 and 2) (Berghauser-Pont & Haupt, 2010). The absence of univocal relations between density, a "gaseous" dimension, and shape, a "solid" though equally variable dimension, depicts both aspects as multipliers of a "liquid" gradient of opportunities, where extracting and examining an array of *n* qualities, each one mated with *m* impacts, is a (complex) designerly task.

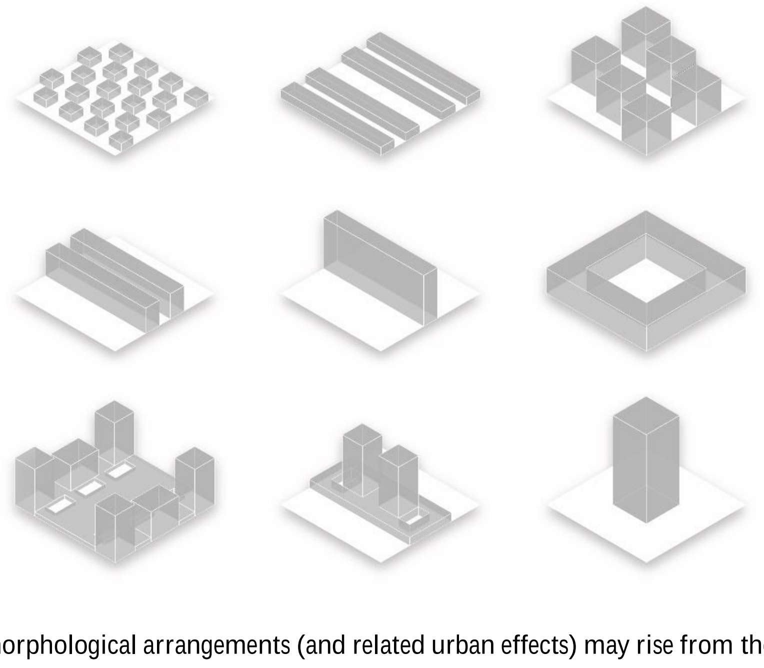


Fig. 1. Very different morphological arrangements (and related urban effects) may rise from the same building potential as an abstract measure of density (elaboration from Falco, 1999).

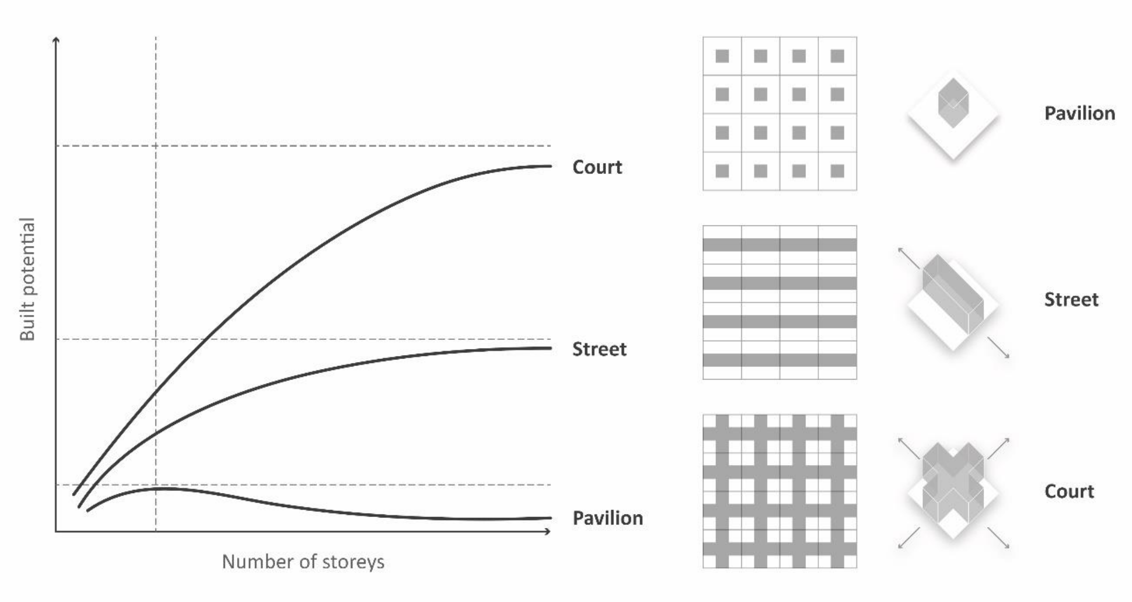


Fig. 2. The lack of correlation between shape and density works both ways: different shape configurations enact unequal behaviors for density increments over the same reference area (elaboration from Martin & March, 1972).

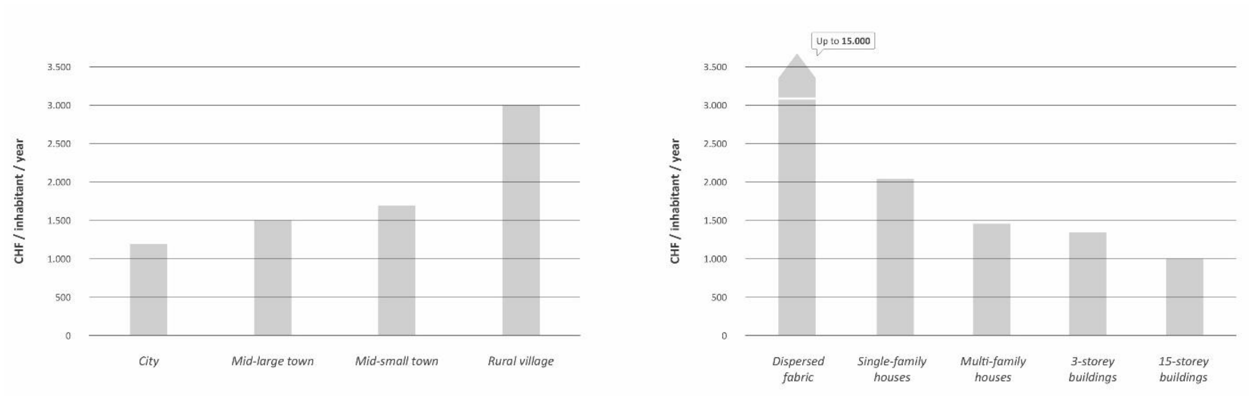
Such compositional problem is a deeply felt aspect for urban scholars who appreciate the importance of form as an influential track on both material and immaterial performance of cities. The product of certain densities coupled with definite shapes, other than being a vehicle of strategic intentions toward political angles of development (Palermo, 2004; Pasqui, 2005), needs to be appreciated in the substantive effects of its geometric quality, unveiling how patterns of volumes through space connote forces of interaction between technosphere and biosphere properties (Fregolent, 2012).

Such patterns are called to tackle massive pressure on both sides of composition, density and shape. The pressure on density levels assumes different, but convergent factors toward intensive exploitation of available land. The challenge to soil consumption is a decisive (and global-scale) match for containing the ecological footprint of cities while preserving important ecosystem services (Paolillo, 2010; Pileri, 2007). Contemporarily, this prospect clashes with rapid and consistent urbanization tendencies: ever more people live in urban, rather than in rural areas. Data show particularly impressive and novel scenarios, with 54% of the world's population residing in urban areas in 2016; in 1950, 30% of global population was urban, and by 2050, 66% is projected to be urban[1]. As the two phenomena collide, planning efficient allocations through densification measures becomes of primary importance.

Compressing spatial occupation by means of density also drives conditions for fruitful socio-economic cycles, which may adopt differing interpretations of benefits based on differing interests. From the standpoint of pure capitalization, private developers may draw higher profits from intensive land use, stretching to the maximum quantity of dwellings per area. Both paucity and locational bonuses of land concur to modulate this propensity (Camagni, 1993). However, density also propagates to public management views, as it plays a quite influential role in predisposing space to at least three benefits. First, it delivers some chance for social encounter, exchange and vibrancy, supporting the attractive potential of an interactive environment for representing communities. At the same time, it naturally reproduces a set of incentives to behavioral change toward reductions in transport externalities, in terms of both carbon and time dispersion. Dense environments, when mated with an organized mix of activities, suggest the transition from total car dependence to a variety of alternative and energy-saving

[1] World Cities Report 2016. Retrieved from http://wcr.unhabitat.org/.

modalities (Owens, 1986), like soft mobility (pedestrian and cycle), public and mass transit (buses, trams, metros, trains), or even car and bike sharing[2]. In turn, these “encouragements” to other forms of investing in movement stand as the counter polarity of a *critical mass* concept. In this respect, we can read density as an essential requirement for installing, supplying and even economizing on urban infrastructures. These features include energy distribution, water provision, and even wastewater and solid waste collection: networks that entail density in return for cost-effectiveness. Both transport and social infrastructures require critical mass as well: density behaves as a fundamental driver for sustaining efficient public transit systems and well-functioning commerce and service facilities, due to their bond with capacity and attraction of users.



Gra. 1. On the left: average cost of the infrastructures (roads, electricity, fresh water and waste water) in Swiss francs/Inhabitants pro year of a city, a mid-large town, a mid-small town and a rural village (left to right). On the right: the same measure with respect to a dispersed fabric, a single-family housing habitat, a multi-family housing habitat, a 3-storey building system and a 15-storey building system (left to right) (elaboration from Frey, 2003).

The pressure on shape configurations consists in the acknowledgement that settling spatial relationships could generate diverse conditions of inhabiting the city. For instance, diverse practices of using space individually or together, diverse ways of perceiving the urban scene, diverse ways of imagining and representing it (Galuzzi & Vitillo, 2009). The research of an equilibrium point between solid and void systems, together with a balance of densities, may achieve a degree of allocative intelligence and efficiency for transformation processes. The compositional problem itself can be expressed as the continuous redefinition of a subtle borderline between principles of spatialization for solids and principles of spatialization for voids[3] (Gabellini, 2001; Selicato & Rotondo, 2009).

We cannot conceive these two aspects of shaping neighborhoods as closed off materials of composition, unless we do not contemplate any mindful organization of built environments. Either we work with one aspect or the other, we cannot afford ignoring their natural semantics. Besides, the contemporary demand for a “recomposing” tension of urban design over contexts of haphazard or scattered growth (Piroddi, 2000) remarks how vital is considering the “logic” of land occupation, more than just its simple magnitude.

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[2] A study conducted by Newman and Kenworthy (1989) has shown interesting evidence about the benefits of urban density within a perspective of sustainable morphology. The study has proven a strict correlation between density (measured in ab/ha) and private transport usage (annual consumption of fuel, in MJ) in urban environments. Denser polarities, such as global megalopolis (Tokyo, Hong Kong, Moscow) and traditional European cities, boast strong cuts to private car usage in confront to Australian and American cities, which share a much frailer concentration. More precisely, higher densities tend to match the substantial reduction of transfers, both in terms of length and number, due to sharper variety of activities. At the same time, this reduction is mated with an ecologically friendly incentive to public transit and soft mobility.

[3] Note that here the term “void” should not to be intended as a literal expression, but, rather, as dregs of qualifying regimes of interaction among solids.

The responsibility of designers increases in parallel with scope and depth of these pressure factors. According to this framework, we can recognize a call for virtuous ways of compacting urban development, with an attention to concurrent criteria of quality that, following the rationalist utopia of the last century, would finally ripen a cultural sensibility for complex values (Mehaffy, 2008; Puerari, 2011).
Leaping "*from the spoon to the city*"[4] does not only mean showing versatile skills, at least not in our perspective. Rather, it stands for experiencing a change of scale that, mirroring sharper complexity (Batty, 2007), inevitably reflects an augmented duty for designers in ethical terms, since the manner we organize the concentration of human life across limited space has profound impacts on social and ecological harmony (Marescotti, 2004). In this respect, the decisive role of morphology as a releaser of sense, quality and integrity for urban environments pushes to the search of flexible design tools for effectively probing that "liquid" gradient of opportunities between densities and shapes, in the attempt at mastering complexity within city molding. Furthermore, the proactive essence of such tools, expressed in backing practitioners during design synthesis, would heavily increase in case of adaptive feedbacks on tuning ductile options. Unlocking a dynamic measurement of such "liquidity" is not an aspect secondary to "platonic" molding, as it would factually approach a strategic efficiency of patterns against precise criteria of performance, taking into account both density factors and different manners of fixing them in relation to a multidimensional domain.

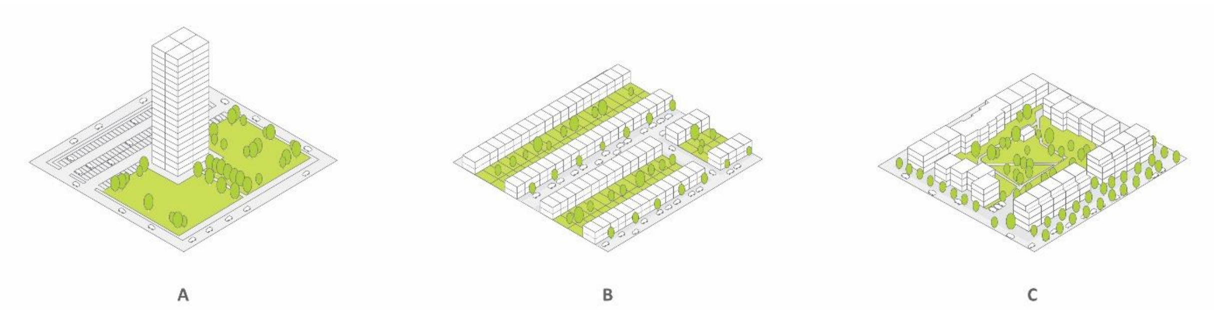

Fig. 3. Through these one-off hypotheses, we notice that the same density load may pool different organization patterns of solid-void relationships, even within the same reference area, which, in this case, amounts to 1 hectare. The arrangements of shape have in common a quantity of 75 dwellings per hectare, but they differ in respect to vertical and horizontal layout. (*A*) shows high building height and low plot coverage; (*B*) low building height and high plot coverage; (*C*) represents a compromise with medium building height and medium plot coverage (elaboration from Mozas & Per, 2006).

0.1.2. The close relationship between *morphology* and *energy* patterns: the challenge of urban design as an energy-conscious practice across different dimensions

The preliminary overview of what we called "compositional problem" portrayed a framework of complex equilibria between the definition of densities and shapes as axes of a matrix assorting different urban effects. Effects more or less desirable according to a varying number of reasons, due to the "polyhedral" nature of city systems (Batty, 2007; cf. Paolillo, 2010). To this point, a reduction of complexity toward more specific remarks on form and energy issues seems important to appreciate the depth of our responsibility for a sustainable future. In fact, the picture we gave is far from being complete.
Speaking about pressure factors on density levels, we have considered the concentration of volume as not only the manifestation of private interests, but also a key provider of critical mass for sustaining what actually constitutes the essence of a city. Aside from supplying the interface among people and institutions (Doherty et al., 2009), concentration contributes to higher resource efficiency, preventing land consumption and energy waste (Puerari, 2011; Rode et al., 2014).

[4] A motto we owe to the renowned architect and scholar Ernesto Nathan Rogers.

Nevertheless, intersecting density with its materialization into proper shape is heavily important as well, given the delicate reactivity of form to complex equilibria. For example, an environment may undergo densification by huge soil sealing, with the risk of retaining heat domes while prompting the overdose of air-cooling systems. Conversely, the idea of containing built coverage with the consistent boost to heights may occur at the expense of building compacity: taller units such as towers typically suffer from disproportionate envelops compared to their volume, triggering the dispersion of heating and cooling loads (Steadman et al., 2009). The transfiguration of higher densities into improper occupation may reproduce a breeding ground for significant overshadowing effects. Together with the previous aspects, the arrangement of volumes should consider emerging "bumps" as potential obstacles to sunlight. As such, overshadowing draws relevance from the aggregate picture of a district, where an interactive play involves more than one unit and has implications in terms of both daylight availability and solar access (Nault, 2016).

Besides, the balance of interstitial voids with solid occupations also tempers heating and illuminance dramatically: sharp densification would require an intelligent design of solid-void systems to preserve outdoor comfort through the control of darkness on the one hand, and reduce artificial heating and lighting through passive strategies on the other. In addition, the effort in curbing heating and lighting demand by geometric properties, such as footprint layout and orientation, does not end up with standard solutions: period and latitude of contexts would suggest the inclusion of summer-winter daylight analysis. Such awareness would be important for devising spatial qualities able to modulate thermal discomfort and sunlight accessibility over critical seasons, so as to invalidate both overheating and overcooling together with the *surplus* of air conditioning and heating, respectively. Natural lighting as well would hugely contribute to softening the abuse of electric devices as reactions to darkness.

Speaking about densities as "primers" of spatial occupation, both in horizontal and vertical sense, the distribution of volumes contributes to calibrating heat dispersion and thermal comfort through sky obstruction as well. In this case, we can appraise the morphological quality of an urban grain even according to the way it carves out sky views from each point of the open space system. As a descriptor of this class of obstructions, which is sensitive to both horizontal and vertical occupation, the *sky view factor* is a seemingly simple, yet refined measure of urban morphometry. Mathematically, it describes the portion of sky visible from each point of observation, with a share that can vary in relation to the geometry of obstructions. Statistically, it correlates built environmental form with the structural propensity to heat island effects (Oke, 1981). As such, it reproduces a simplified model for judging the aptitude of voids for reflecting daily heat loads, based on solid pressure. Thanks to its good approximation, such measure may result extremely helpful in fostering outdoor comfort while containing the recourse to indoor cooling in the summer.

According to the estimates of the World Bank, both artificial heating and lighting of buildings produce a quarter of the global emission of greenhouse gases[5]. Thus, we should spend some time studying alternative arrangements of aggregate, district-level forms of the built environment. In parallel, transport counts for a third of the energy waste characterizing urban areas. Choosing appropriate densities in combination with (equally appropriate) shapes becomes a fundamental task for sustainability, given the basic requirements for supplying energy-saving modalities (Owens, 1986). For instance, transportation is responsible for 60% of the CO_2 emissions in São Paulo as opposed to only 20% in London and New York: cities well served by underground systems that structurally count on huge densities (Montavon, 2010).

These complex equilibria confirm that the geometric properties of patterns, which we can re-interpret in terms of *horizontal* and *vertical obstructions* of space, perform as powerful instruments for controlling outdoor comfort, local microclimate and even the energy consumption of building units[6] (Adolphe, 2001). The French journalist Grégoire Allix (2009) declared the fundamental role of cities as a solution to, rather than the problem of,

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[5] Retrieved from http://projects.worldbank.org/.

[6] This also means that shaping the built environment at the district level confers a decisive role to urban design and masterplanning, given the strong impact of aggregate patterns on both energy demand and supply modulation. It follows that

climate change: compactness combining housing and activities served by fitting public transit provision boasts a sharp reduction of ecological footprints compared to secluded and scattered housing, which relies largely on private vehicles (cf. Owens, 1986). It follows that, at least from the standpoint of sustainable and environmentally friendly development, the compact city is considered as a desirable model. Nonetheless, the complex equilibria connected to densities and shape conformations release an interacting series of influent trade-offs with respect to the energy performance of urban form.

0.1.3. Recognizing some relevant "pre-parametric" studies as informers of compositional efficiency: addressing solid-void occupation patterns and their solar implications

Before deepening the scope of our interests, we may dedicate some time to appreciate the compositional problem, and its energy implications in particular, as an experience rooted into urban design speculation over time. We do not intend this section to be an exhaustive review of pre-parametric attempts to address the articulation of densities and shapes for energy-conscious spaces. However, the examples we selected for this purpose, while being dissimilar in the approach, share the ambition to polish land use efficiency through the alternative design of dense environments.

Walter Gropius (1966) has actively participated to the theoretical speculations of Modern Movement, together with other milestones such as Le Corbusier (1887-1965) and Ludwig Hilberseimer (1885-1967). The architect sought to prescribe universal composition rules, starting from the firm stigmatization of traditional and block-based fabrics as sources of wider occupation of land in return of a scarce daylighting performance. As an alternative to closed yards, which he believed to be unfavorable in terms of natural light permeability, he considered a parallel block development based on rational slabs, which would have thinned out settlement patterns toward the balance of Sun exposure. Nowadays, the recognition of complex equilibria as values for urban quality would consider the mechanical devotion to *one* single design criterion as a rather simplistic approach (cf. Montavon, 2010). Anyway, we should credit Gropius with a systematic effort in studying density increments in close relation to the energy feedback of shapes and their solid-void systems.

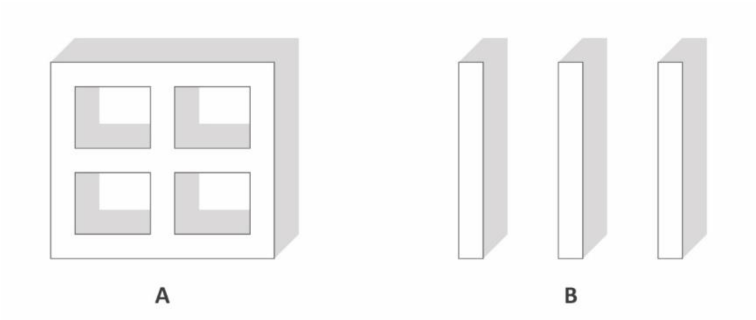

Fig. 4. From perimeter block patterns (*A*) to parallel slab patterns (*B*) (elaboration from Stevens, 1990).

According to his view, organizing rules for molding at least the extent and spacing of obstructions, even though using preset urban types and orientations, would have unleashed the active reaction of efficiency measures to every modular shift of densities. This "trick" provided Gropius with a simple but instructive method for probing the balance between densities and shapes, where efficiency stood for the highest possible concentration of inhabitants at the lowest expense of daylighting conditions. The German architect conceived basic testers made up of four elements: *1*) site area; *2*) sunlight incidence at the base of buildings in winter; *3*) number of inhabitants; *4*) slabs unlocked in the *z* dimension.

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it is not enough to conceive energy-saving strategies and actions at the scale of single units, as this reference "frame", other than reproducing sectorial decision styles, fails at considering the relevance of aggregate energies (Pareglio et al., 2012).

At the same time, the rational mix of three standard rules would have driven the balance of alternative options toward more preferable solutions (Montavon, 2010). The *1st* rule stated that, keeping both site area and sunlight incidence constant, one could attain higher densities by means of increasing the number of floors[7]. The *2nd* rule stated that, keeping both sunlight incidence and inhabitants constant, one could achieve the contraction of site area requirements by means of increasing the number of floors. The *3rd* rule stated that, keeping both site extent and people constant, one could achieve the decrease of sunlight incidence by means of increasing the number of floors, with the "dissipation" of obstructive strains, wider elbow-rooms for mutual spacing and sizeable gains in open space coverage. As we can notice, each rule acted as the combinatorial "negative" of the others.

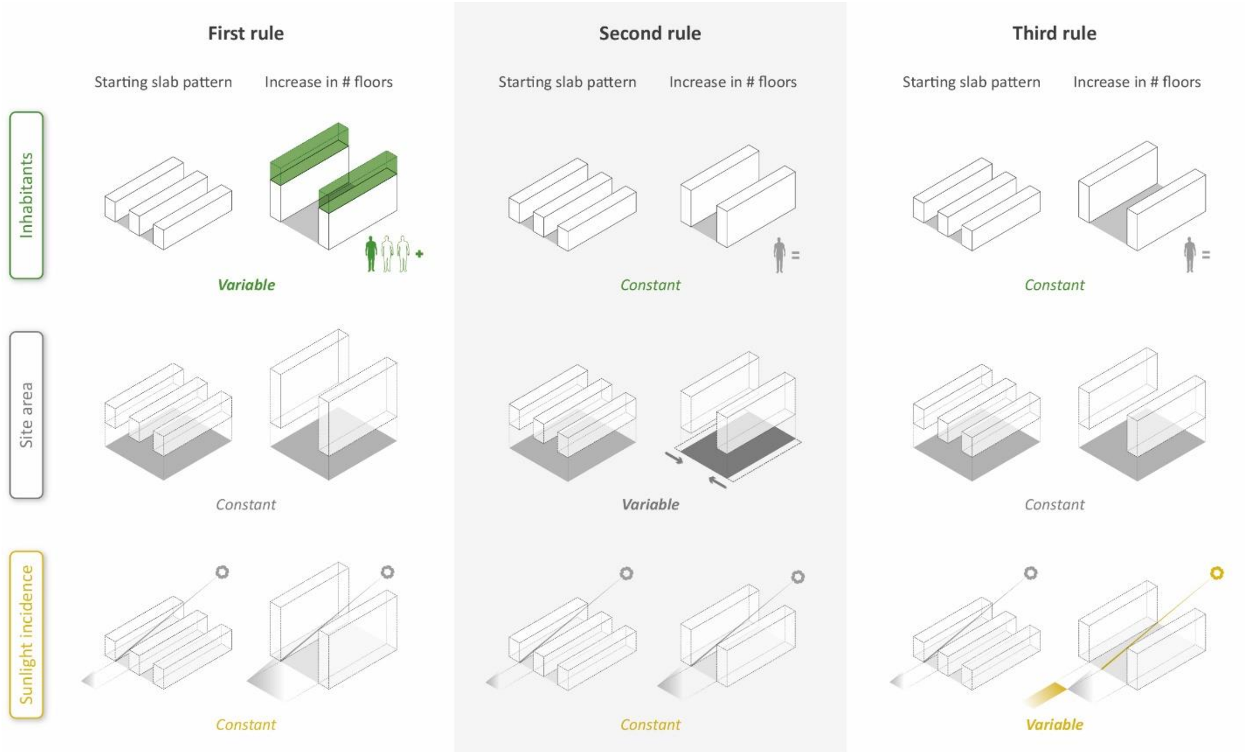


Fig. 5. Walter Gropius. The matrix of rules devised for his basic testers. Each of the three rules reproduced a different interplay of constraints to population density, site area and sunlight incidence at every increase in floor number, depicting different declinations of efficient pattern with no expense for residual criteria. We can have densification (at the top left corner), reduction of necessary space for development (in the middle), and elbow-rooms for open space per capita, the latter stemming from the exclusion of voids from being functions of sunlight incidence (at the bottom right corner) (source: author).

Gropius put different intersections of variable and constant elements to the test, claiming that high-rise buildings used available land more efficiently than lower rise units did, at least in terms of quantity (Gropius, 1966; Montavon, 2010). Based on his findings, the architect found the optimal height for parallel block patterns at 10 to 12 floors, which he considered as preferable to 3-, 4- or 5-storey slabs against the simple criteria chosen for the evaluation. Stretching building units up to 12 floors proved to be a preferable solution, as it achieved the highest population density compared to the preservation of an elbow-room for natural light.
A complementary, yet equally interesting aspect of efficiency regarded open space provision: in fact, approaching optimal heights generated the increase in amount of open space *per capita* (Gropius, 1966). However, two observations need to be made with respect to this latter aspect. First, since urban types describe distinct density curves at floor increments (Martin & March, 1972), we should keep in mind that such findings for open space

[7] Read *vertical obstruction*.

provision only refer to one particular solid-void regime: in other words, a different typology would have correlated the growth of citizens and spatial extents in a proportionally different way. Second, as Montavon (2010) warns in her research study, the *quality* of space is as relevant as its *quantity*. Open spaces (voids) are extremely sensitive to their enclosing environment (solids) as they influence and absorb it in an osmotic fashion. Smaller voids between low-rise blocks may offer livability conditions for the local community that, in some cases, may be more adequate than large spaces built only for the sake of absolute and supposedly desirable standards.

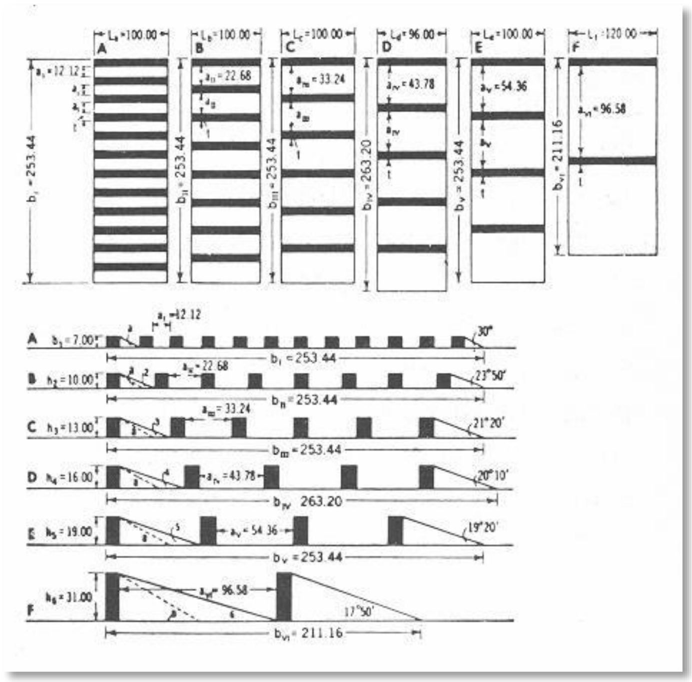


Fig. 6. Rational design of settlements made up of parallel slabs, by Walter Gropius. The cumulative mixture of the three compositional rules helped defining solutions that raised building potentials up to an equilibrium point where a healthy amount of sunshine was achieved together with the containment of plot sizes (source: Ruano, 1999).

Unlike Gropius, Leslie Martin, Lionel March (1972) and Michael Trace (1968), widened the scope of efficiency through the involvement of other solid-void patterns, with no sort of Modernist prejudice toward block-based options. In the late 1960s, the three researchers from Cambridge worked on the definition of optimal land use according to two quantifiable measures: floor-to-area ratio on one hand, and daylight availability on the other. Measures that plainly exemplified the problem of a compromise between certain levels of density and the spatial dimension of energies. The English scholars examined different ways of obstructing available space through the articulation of archetypal forms. The choice of simplified typologies has been particularly helpful in reducing the complexity of real urban textures at a time when computing power was still limited. Probing and comparing the influence of geometry alone would have led to an easier interpretation of results, due to the abstraction of solid-void relationships (Ratti et al., 2003).

At first, the study focused on two arrangements rising from the uniform repetition of, respectively, courtyards and pavilions. The formers resembled the traditional forms of occupation we are still accustomed to in many Countries, while the latter reflected a reverse space system (cf. Carmona, 2010), made up of those free-standing towers that became popular after the Modern Movement. Later on, the investigation involved a third elementary form, the street, which represented a nonstop row-house extension. With respect to the outcome of iterations, the pavilion could be considered as a finite form submerged into pervasive open spaces; the street could extend infinitely along one axis, splitting open space into successive stripes; the court could reproduce a sharper articulation of open spaces into framed lots, through a potentially infinite extension along two axes.

Starting from the three archetypes, the researchers pursued a combinatorial assembly of six alternative schemes for solid-void systems. In a paper by March and Trace (1968), we find the comparative appraisal of these alternatives against the two dimensions of morphometric efficiency: respectively, the ability to accommodate higher building potential and to guarantee adequate daylighting provision.
Following the examination of bonuses and maluses for each of the two measures, the scholars observed that land use performance improved with geometric circumference, meaning that courtyards performed better than rows and pavilions.

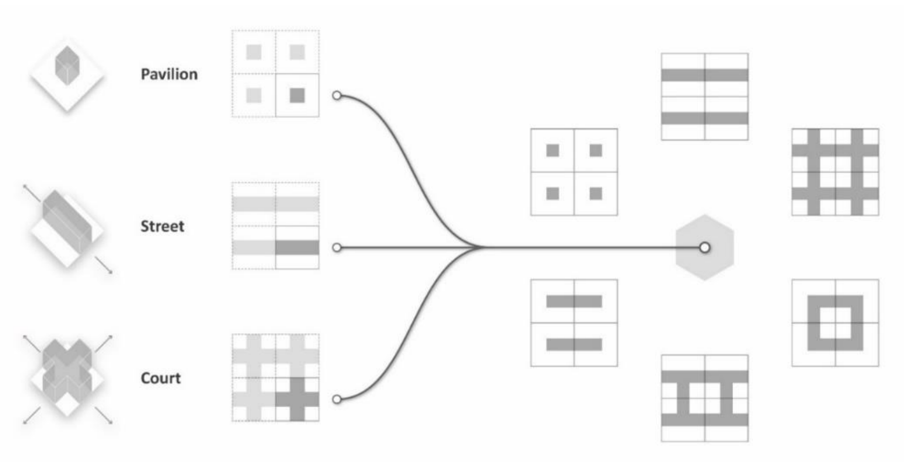


Fig. 7. Leslie Martin and Lionel March. The assembly of generic urban forms, starting from three elementary typologies: a detached occupation (pavilion), a bi-directional concatenation of "puzzle pieces" (courtyard) and a mono-directional alignment (street) (on the left). The assembly took place by aggregation of the same type per pattern on one side, and by combination of more than one type per pattern on the other. From the top left corner going clockwise: pavilions, slabs, courts, pavilion-courts, terrace-courts, terraces (elaboration from Martin & March, 1972).

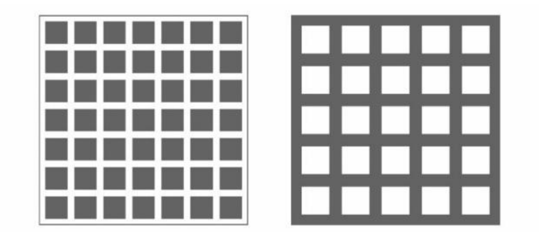


Fig. 8. Leslie Martin and Lionel March. Two archetypal figure-ground patterns: one based on standalone pavilions (on the left) and the other based on courts. Both samples share site coverage, building height and total floor space, but the court-based approach has shown a better compromise between land use intensity and daylighting potential (elaboration from Ratti et al., 2003).

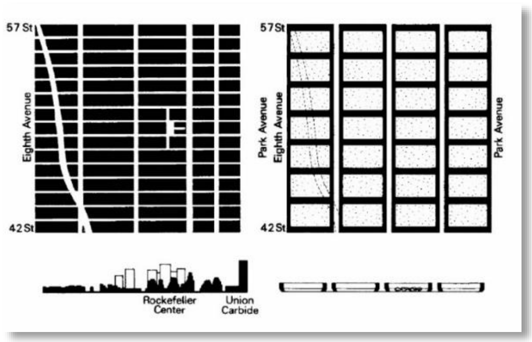


Fig. 9. Leslie Martin and Lionel March's (1972) provocative hypothesis to replace the pavilion-based pattern of a part of central Manhattan with large courts, given the result of their analysis. The proposal would have provided exactly the same amount of floor area while carving out larger voids and, at the same time, reducing the height of buildings from an average of 21 storeys to 7 (source: Ratti et al., 2003).

This result does not necessarily contradict Gropius' findings for parallel slabs. Here we face a crucial aspect of modeling with preset conditions, something that, as we will see in the next parts, hugely determines both parametric synthesis and evaluation of form[8]. Defining specific conditions as a discipline for shaping sample environments is a deliberate choice, and a delicate one of that, because assessment measures insist on the product of that choice, however objective it may be[9].

The last of this non-exhaustive series of contributions refers to a refined effort in addressing the conformation of shapes within a framework of neutrality between densities and solar obstructions. The fundamental concept of *solar envelop*, insofar as Ralph Knowles has conceived it (2003), is central to this accomplishment. Developed and tested at the University of Southern California (USC), solar envelops give explicit conditions to the generation of shapes, based on imaginary boundaries derived from the relative motion of the Sun.

The author considers these "bounding boxes" as a construct of space and time (Knowles, 2003, p. 16). For every designed plot, a solar envelop illustrates the *locus* of all the occupations that would assure sunlight access to bordering volumes over a specified span. Both final size and shape of an envelop stem from the combination of these two measures, i.e. geometries of surrounding buildings and interval of sunshine warranty. The idea of "neutralizing" the conflicts related to densities and solar obstructions plays a crucial role in interpreting such warranty as a source of efficient design of occupations. More specifically, a solar envelop articulates the concept of land use efficiency as the maximum outlet of density pressures that we could grasp without any risk of veiling surroundings over critical periods for passive architecture. As the calculation of solar envelops shaves optimal boundaries against a predefined goal, always expressed in terms of space-time settings, we can even appreciate a quite relevant shift compared to the previous studies, at least from a purely procedural perspective. In fact, what we experience here in relation to shaping and reshaping with rules is not anymore a step-by-step tuning of conditions, such as marginal increase in floor number or alternative choice of types; rather, it is the "*inverse*" determination of final form[10] (cf. Vanegas et al., 2012). This logic, though leaving room for a degree of freedom in actual design, helps sustaining the tension toward maximum densities with minimum obstruction over context features, instructing shape patterns through an intuitive and non-banal link with the visible transfiguration of site and time-specific carrying capacities. In line with the concept of inverse determination, it is vital to note that solar envelops, while conferring a more or less faint shape to density itself, define carrying capacities as if they were directly forged by the Sun, meaning that they represent the aftermath of a calculated appraisal, more than a starting point in the hands of designers. As envelops respond to the demand of contexts, their geometric properties, consisting in a volume and its so-called *shadow fences* (Knowles, 2003), should rather be interpreted as the result of a rule that internalizes a process of scrutiny over the expected access to sunshine.

An equally relevant point is that shadow fences represent a *Pareto-efficient* allocation of density loads (cf. Balling et al., 1999), serving as precise boundaries beyond which designed occupations would disrespect either or both site and time-specific rules imposed to shadow casting. Fences are highly *responsive* systems of warranty, as they adapt to any possible configuration of neighboring shapes and time constraints; in turn, the two options would instruct as many relationships with the simulated behavior of Sun paths. From the standpoint of space

[8] More specifically, we will refer to this methodological aspect in Part III, speaking about practical experiences of compositional solving through parametric and algorithmic design.

[9] As a matter of fact, we cannot compare the outcomes of the two studies, because each of them simply adapts to different ways of informing obstructions with rules. For historical and cultural reasons, Gropius denied the chance to revisit traditional blocks with an *a priori* endorsement of parallel slabs and vertical orientations, but at the same time, specifying the interaction of solids and voids as a dynamic matrix of variable elements. Such matrix did not take place in Martin, March and Trace, except for a fixed, but assorted series of typologies across space, each with one distinct solid-void logic, including block-based arrangements.

[10] This aspect anticipates a fundamental distinction within a parametric design domain, something that will lead to consider alternative approaches for improving efficient occupation. With respect to the involvement of rules into compositional problems, we will recognize two options: fine-tuning (or *forward design*) and optimization (indeed, *inverse design*). See section 1.3.4.

criteria, the calculation may consider selected windows or walled systems, not necessarily the neighborhood as a whole. The relative tallness and distortion of fences may also react to particular functions: for instance, housing may demand a certain degree of pietas compared to commercial and industrial activities, lowering obstructive tensions according to the location of resident units. The total size of solar envelops, and thus their relative building potential, varies with street orientation too. The importance of street patterns in our relationship with the Sun has been explored quite extensively across the literature (Van Esch et al., 2012). But, at the same time, we cannot deny the achievement of envelops in informing spatial occupation with a three-dimensional picture of the effects connected to such latent, but vital relationship. Time criteria have an influence as well, due to the relative motion of the Sun either on a daily basis or over strategically or statistically critical periods, such as the hottest week of summer or the coldest week of winter. These calculations embody what the author calls *cut-off times* (Knowles, 2003) as a temporal domain for the emergence of volume loads. Results describe, in this sense, the accomplishment of the largest theoretical container of volume that would avoid casting off-site shadows not only over space thresholds, but also within the specified span. Of course, the appealing idea of "a maximum volume" cannot be fully embraced without considering the extent to which changes in time settings may trigger the fluctuation of this maximum. This is another declination of rules as inescapable determinants of outcomes: the bond between cut-off times and the Sun as a molder of urban form implies a natural impact on the gradient of solutions, due to both entity and coincidence of constraints. It is evident that longer periods of assured solar access would be much more constraining on solar envelops than shorter periods (Knowles, 2003).

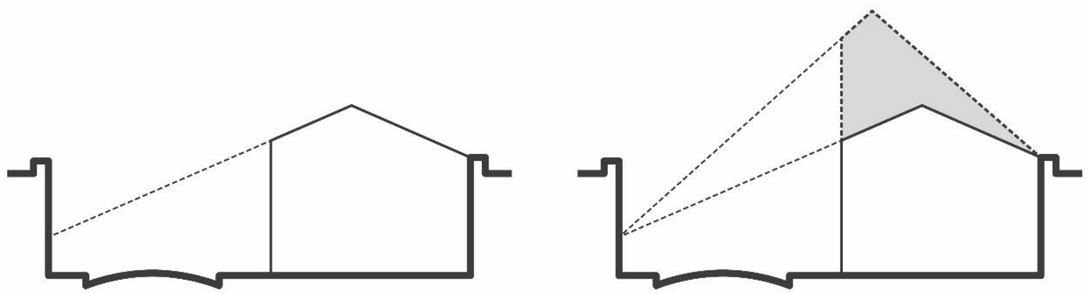


Fig. 10. Space–time constraints deeply affect the final geometry of envelops. Preliminary conditions may instruct fences so that they have different heights on adjacent properties to avoid overshadowing elements such as windows, façades or rooftops, which could not benefit from direct sunshine otherwise (on the left). Modifying cut-off times implies the increase (or decrease) of volume under the envelope, due to their inevitable relation with different sun angles (on the right) (elaboration from Knowles, 2003).

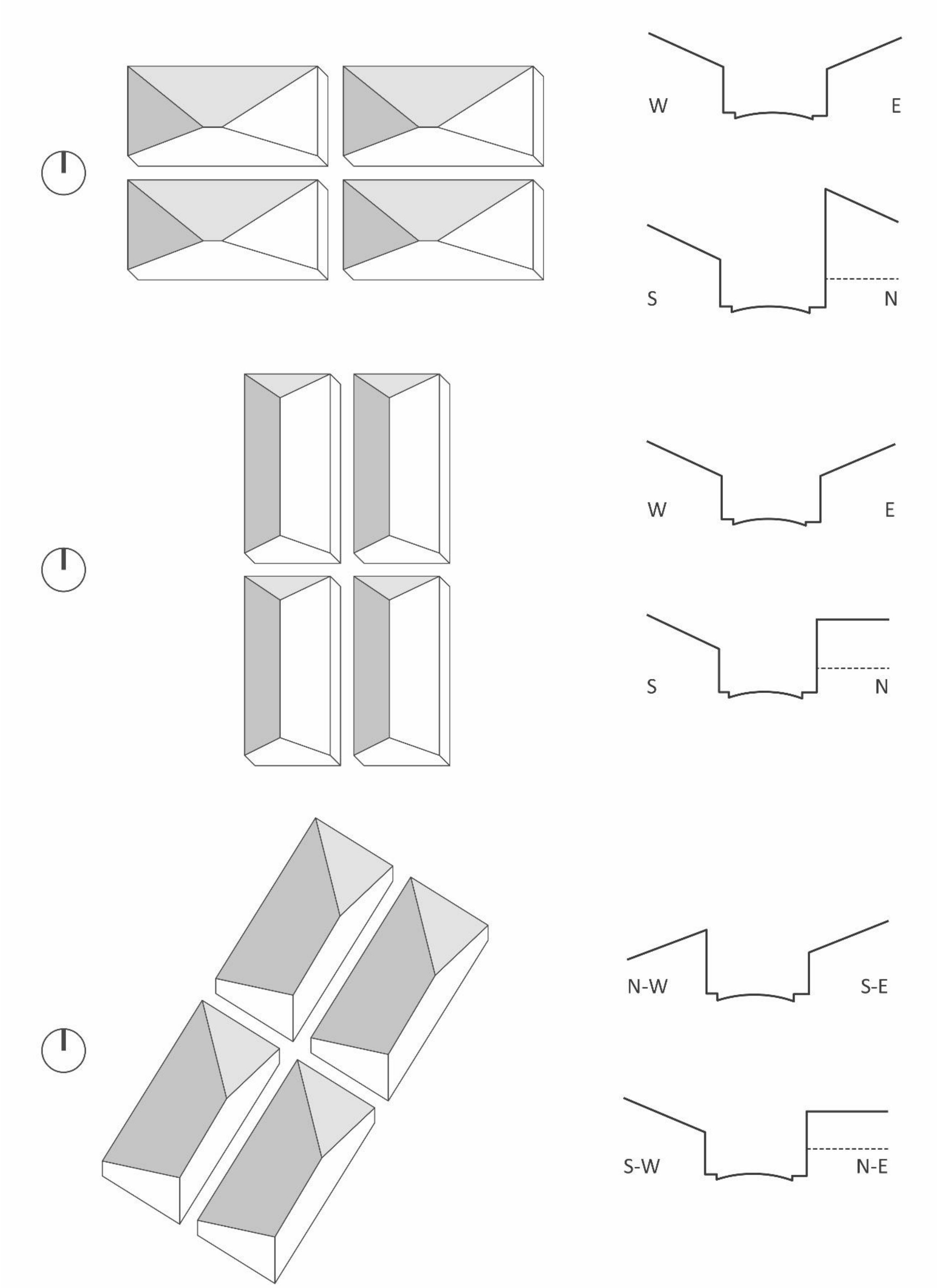
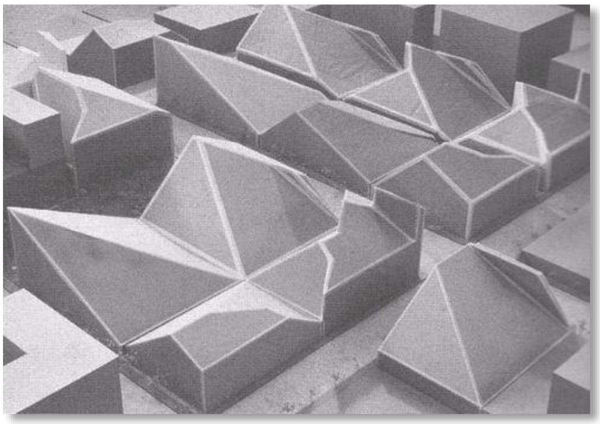


Fig. 11. The influence of street orientation. Here we observe three different block orientations, each demonstrating the relative effect on both size and shape of solar envelops. Envelops covering E–W blocks have the most volume and the highest ridge, generally located along the South boundary (at the top); N–S blocks destine less volume and a lower ridge running length-wise (in the middle); diagonal blocks yield the least volume and a ridge along the South-East boundary (at the bottom) (elaboration from Knowles, 2003).

The relative importance of envelops within our thematization framework should not be taken as some sort of an ancillary aspect in addressing the compositional problem through an energy-conscious balance of densities and shapes. In fact, both tallness and distortion of shadow fences, while constraining size and outline of each solar envelop, limit the burden of composition by means of a "basin" able at least to enclose the extent of our "liquid" gradient of urban solutions, with a sound and operative sensibility for efficient occupation.



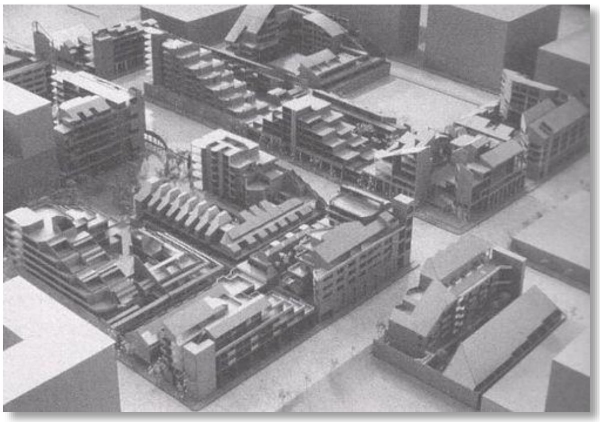


Fig. 12. An operative example of solar envelops pledged to the efficient occupation of a housing project. As we observe it from the east, this test-bed consists in multiple plots with housing over street-front shops. In this case, solar envelops provide 6 hours of sunlight access above a 20 feet shadow fence at neighboring properties (on the left); all volumes taking place under the envelop guarantee at least 4 hours of solar access and cross-ventilation for each building unit (on the right) (retrieved from http://www.resilience.org/).

0.1.4. Appreciating parametric design environment as a support system for exploring the morpho-energetic dimension, leveraging the shift from *discrete* to *continuous* massing

Ignoring the influence of geometries in determining the equilibrium of energies would invalidate any perspective of sustainable city making. Adopting the solar performance of compositional grains as our main focus, we cannot imagine well-functioning strategies neither for active reception of sunlight, nor for satisfactory daylight provision, without questioning the passive syntax of obstructions at up-scaled neighborhood levels[11]. There we find the appropriate ground for investigation, where the degree of modeling complexity reflects the importance of predisposing forms in their combined essence, so as to shoulder the inevitable conflicts of occupation among single architectures. However, the refinement of form toward an energy-savvy "intelligence" also needs adequate techniques to solve (or at least address) compositional problems among densities, shapes and solar outcomes. In other words, to support designers in finding (or approaching) an efficient order of obstructions over the three dimensions, coping with their ethical accountability in relation to consumption patterns.
The approximation of "maximum" efficiency is, clearly, something tremendously far from trivial problem solving. Rather, it would require the compilation of catalogs comprising ever more subtle combinations of generic models, each one connected to a likewise subtle shift in terms of passive performance. This effort in permuting forms at high combinative resolution would be essential for probing spatial properties, especially according to

[11] As Montavon (2010) observes, architectural and planning practice tend to affirm their protagonist role in managing the complexity of environmental issues as one of their most compelling duties. Nonetheless, this does not necessarily translate intentions into the most suitable solutions for solar design. Typically, this is due to the common "inertia" of institutions, policies and other interested parties in questioning the central role of urban morphology, despite their factual (or declared) support to a rational use of energy.

alternative selections of compositional facets. For example, we could practice the modification of shapes, keeping densities as constant features: this option would enable the comparison of results in terms of layout qualities rather than quantities alone. Its "negative" would consist in comparing the distinct reactions of every shape at increasing or decreasing densities. Perhaps the most fertile option would consider the dual variation of densities and shapes in a heuristic search for layout efficiency, based on the relative importance we attach to every aspect of composition.

It follows that such techniques would acquire particular value from their ability to correlate both densities and shapes as "fluid" informers of final morphology, in the attempt to govern the "liquid" gradient of compositional opportunities. More specifically, this value would consist in sizing and distributing both horizontal and vertical obstructions elastically, allowing for adaptive evaluation of free solar gains and, at the same time, dumping the prohibitive efforts required for reproducing detailed transitions from a model instance to the consecutive one. In this perspective, an approach able to go beyond the appreciation of *discrete* instances to a *continuous* display of transitions may be a powerful tool for achieving the resolution of our compositional gradient. In this respect, we can consider *parameterization* as an interesting expedient for exploding occupation toward fugitive geometries, harboring their whole set of intermediate shades. Conferring a parametric domain to morphologies acts, in this sense, as a paradigmatic conversion from *specific* conceptions of form, either urban or architectural, to what we imagine as a *generalized* massing system.

Parametric design technology soundly represents this change from discrete to continuous massing, conceiving form and its obstructive property as an explicit function of a number of parameters. This suggests that densities and shapes may liberate themselves from preconceived figures of materialization, depicting the emergence of spatialities that are ductile and organic, since these respond to every alteration of parameters in real-time.

> *«Instead of assembling rigid and hermetic geometric figures [...] parametrics bring malleable components into a dynamical play of mutual responsiveness as well as contextual adaptation. Key design processes are variation and correlation»* (Schumacher, 2010).

These models adapt to *variations* autonomously, because parametric "*stimuli*" propagate across a system that *correlates* them with outcome geometry. Thanks to the genotype of such *constraint system*, which is defined by parameters and processing options, volumes assume self-organized phenotypes that spontaneously react to the complex interactions existing among their constitutive elements[12]. As the genotype is what informs the array of possible phenotypes, we recognize that the forms we observe are not the starting point for achieving efficiency, but rather the unknown variable of an equation made up of precise rules of occupation. Designing itself becomes a project of "*intelligent rules*" (Fusero et al., 2013, p. 5) that are set up to sustain variation and correlation of the system as a whole.

[12] The common "kin" between parametric design and biological systems is not something ending up with a poetic interpretation of theory. In contrast, it has been driving research toward ever more sophisticated forms, using genotypic rules of construction as a ground for incorporating the intelligence of nature and transmitting its structural qualities to human artifacts. *Biomimicry* probably stands for the highest degree of osmosis between the two fields of knowledge, where parametric rules are designed to emulate natural processes of growth and their adaptation to challenging contexts, such as the ecologically impaired world of the future (Leach, 2009). However, we will also see that this biological analogy will permeate a central discussion upon *generative* processes in parametric modeling and their path toward optimizing solutions.

Harnessing the snowballing potential of computing, parametrics may open new windows to design discipline, through a revolutionary shift from typological to procedural thinking. In fact, we owe such continuous regime of transitions to a novel focus on the *process* through which forms come to be, interpreting standard or accustomed solutions as the tip of the iceberg, if compared to a parameterized range of opportunities. This process-oriented philosophy is actually the key to continuous massing, because modifying how the process is informed means delving into an evolution course whose outcome does not "freeze" into one discrete instance; rather, it sustains a matrix of virtually endless alternatives, which we can slide across elastic (or "liquid") ranges of variation.

> *«Embedded in this method of exploration is the idea of capturing design history and returning it in an editable form, which can be varied and then re-played. The power of the concept is the belief that design history can be extrapolated to produce design futures»* (Whitehead in Woodbury, 2010, p. 49).

The very act of governing outcomes through their genetic process supports basic variation as well as the combination of diverse correlation patterns, leading to gradients that may expand the manifold nature and the fine-grained resolution of alternatives. Controlling the underlying process of formal generation becomes central for unlocking several intermediate "inflections" of form that are not practically accessible through standard typologies (Woodbury, 2010).

> *«The history of design can be read as a constantly changing process of exploring for new form-generating ideas, using whatever tools and intellectual concept are at hand. New languages and styles of design require such exploratory play, especially at their early stages»* (Woodbury, 2010, p. 39).

However, managing the process is not only a stratagem for widening morphological contemplation. As we link the range of solutions[13] to that equation to the assessment of their geometric properties, we set the basis for de-quantizing structural performance. This is a crucial liaison, because supporting evaluation through the evolution course of a process allows for sifting the stream of its outcomes toward adequate selections. These selections, while being consistent with specific rules, would represent an improved intelligence in configuring parametric settings. In other words, they would be the image of settings needed to realize desirable or even optimal outcomes, with respect to certain ideas of quality[14].
As we imagine the chance of informing occupation through a parametric system, this aspect may have relevant implications for addressing the compositional problem. In this light, coordinating parameters would serve as a linchpin for calibrating solid-void gradients, in search of more efficient equilibria between entity of occupations, quality of geometric properties and solar consequences. Given such premise, we may imagine a compaction strategy that, based on virtuous combinations of density with shape, would not necessarily impair daylight and sunlight potential, contrary to what we generally presume (Montavon, 2010). Other than providing dense environments, controlling volumes parametrically would also consider sharpening the geometry of depths and heights in relation to dynamic energy feedbacks: in this perspective, one could manipulate values so that outcome occupations verge on energy balance through minimized consumption and proportionate accrual of solar energy on site. Given the range of possible outcomes, one (or some) of them, stemming from selected values of parameters, would correspond (or approach) to the pattern maximizing natural daylight or sunlight for the whole intervention.

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[13] Other terms may be "*solution space*" or "*solution set*", as suggested in Aish (2005) and Fraser (2012) respectively.
[14] As a result of this process-oriented perspective, designers can visualize and compare fluid alternatives by simply sliding parametric settings, paving the way even to an increased consciousness of the effects that their own rules and values may have on outcome performance. An opportunity that becomes explicit as far as we dump static analytical models in favor of a dynamic and integrated connection between "genes" of form and evaluation cycles.

As we can notice, endorsing the design of processes toward "transient" massing breaks through the barriers of preconceived types (cf. Knippers, 2013). Process-oriented approaches show a natural predisposition to exploding occupation patterns over a gradient of opportunities, something that may have important implications for probing the complex and indeterminate space we find between densities, shapes and energies. Besides, as processes couple reactive evaluation systems with the continuous modulation of parametric changes, we may assist to a proportionally detailed resolution of energy feedbacks, leading to an unprecedented management of structural qualities.

Generating these "decimal" streams of possible outcomes assumes, clearly, a distinctive way of thinking (Knippers, 2013). This goes well beyond the simple use of advanced software. Parametrics denote a reversed attitude to the generation of form, compared to what we experience with conventional modeling. Being borrowed from mechanical systems, the link between process design and structural performance becomes clear, but it may also seem alien to architects and urban designers used to creative reshuffles of tangible outcomes. Hugh Whitehead puts this shift of paradigm in a lyrical way, recognizing some sort of parallelism with musical harmony as opposed to seemingly alike, but methodically different forms of art:

> *«As a concept, parametrics is far more likely to be understood by a musician than by another type of artist. This is because the musician is dedicated to rehearsing of performance, which is an essential characteristic of a virtuoso in parametrics. To another artist, on the other hand, the accumulation of technique is incidental to the production of an artifact, which is the result of direct interaction with a medium. For this activity there is no written score that can be fine-tuned and re-played»* (Whitehead in Woodbury, 2010, p. 49).

So far, we have been assimilating architects and urban designers to this residual category, in which adjustments to form come about as one-by-one attempts at sketching solid outcomes, rather than grasping their core logics of emergence as an expedient for handling compositional properties dynamically. Nevertheless, we may yet see the rise of novel generations of designers pledged to inform the growth process of morphology with intelligent rules, as the increasing connubial with computing technologies comes to our mind[15].

[15] This does not mean, however, that such generation will experience an immediate mastery of parametric thought. From a methodological standpoint, we will see that parametrics require much practice before achieving a degree of fluency, due mainly to the inertia in re-adapting accustomed rationality, the compatibility of intuition with a correlation vocabulary and the inevitably discretionary selection of rules for generating outcome geometries.

0.1.5. The expected goal: reconstructing a theoretical framework and outlining prospects and obstacles of an integrated approach to parameterized composition feedbacks

Before deepening our discourse upon parametrics as a support system for governing the complex equilibria of spatial occupation, it may be right and proper to first clarify what the thesis *is not*. It is important to understand that our aim is actually far from "sponsoring" a novel technique independently from tangible design needs and finalizations. Aside from alleging the "embryonic womb" of parametrics within planning fields (Steinø et al., 2013), we do not intend depicting this application as a source of uncritical and contemplative scientism. We consider the discourse upon such distinctive methodology as neither an occasional fashion[16] nor the definitive solution, nor even the "right" model for managing the complexity of shape-density compositions and calibration. Let us suppose, rather, that a humble, but serious endeavor to address morpho-efficient occupation should start from conceiving every approach as part of a wider technical equipment, called to deal with the inherent complexity of built environments through the integration of their feedbacks[17] (cf. Cecchini, 1999).

As recalled by the American planner Britton Harris (1968), all models are always "models of" or "models for". For this reason, they need some sort of scrutiny and validation along a practical axis as well. According to this framework of mind, we intentionally choose not to lie on the "empyrean" of pure theory, where criticism and operational boundaries do not seem to count as much as they should (cf. Zarei, 2012), because we understand that knowledge and learning draw their fuel from that cognitive space stemming from the osmosis of theory and practice.

First, we manifest the attempt at reconstructing a theoretical framework. This basic aspect comes from the lack of a systematic review of salient characters and evolution steps in parametrics, especially considering the widening scope toward complex performance measures. This follows nothing but Wassim Jabi's (2007) interesting argument in stigmatizing the field as profoundly plagued by fragmentation. No clear research taxonomy nor a solid base of manuals or peer-reviewed protocols for an ordered and sequential stream of assumptions, reflections and findings seems to be shared and recognizable across the scientific community (Fraser, 2012). Unlike structured fields of knowledge, parametrics tend to resemble a nebula of parallel studies and echoes, devoid of any hallmark author or "manual" of reference.

Such preliminary framework for theory, aside from summarizing the salient features of modeling through parameters, would pave the way to diverse finalizations to probing the compositional gradient and its high-resolution space of performance, with a particular regard for morpho-energetic efficiency. In this perspective, we hope to re-establish a "function" over mere "fashion" (cf. Fraser, 2012) with a look at an urban design guidance purpose. Parametrics may establish some sort of affinity with a straightforward government of complexity that goes beyond "facelift" aesthetics: it goes where technology helps engineer design interface by injecting substantial, structural qualities into the bowels of form. This novel and augmented interface would concatenate functions decisive for managing how geometries behave, that is, how they prepare to physical standards, not (only) how they look like. In this framework, disciplines like product design and engineering have been drawing huge

[16] It is not an ephemeral fashion due to the consistent, increasing and ever more recognizable diffusion of new computing technologies and their virtual reconstruction of technospherical and biospherical environments, which have been acquiring relevance from a disciplinary, as well as curricular point of view for the sake of analytical rigor and informed design.

[17] Other than being non-neutral supports, models and methods perform an inevitable (but manageable) reduction of complexity along one or few dimensions of urban reality, by means of a reasonable reduction of variables under examination. The integration of instruments matches a perspective of synergic coherence, which is grounded on requisites of technological interoperability, becomes indispensable for re-assembling the original aspect of complexity, even though with all the limits that may arise from time and attention, where re-assembling means a conscious "puzzle-box" laden with a clear speculation and finalization. In this respect, our case will be an input for managing the manifold complexity of form and its responsive evaluation through dedicate software, waiting for further ameliorations toward realistic support and information for masterplanning.

benefits: we can mention, for instance, the increasing "friendliness" of components, but also the extensive convergence of basic functions and desired forms, which is ever more probable at lower complexities (Zarei, 2012). As we come to areas like architecture and planning, convergence fades into blurred horizons, where constraints have to carefully adapt to more than a few factors. At this point, it seems vital to find new meanings for parametric knowledge, and start questioning whether the same approach is still suitable or not within a context of greater complexity. Here, the compositional problem is proposed as one possible thematization for parametric and urban design activities. Yet, transposing the model to urban space does not imply that solutions are as easy to obtain (Fraser, 2012). Theoretical literature seems not to help us enough in this sense, as it generally focuses more on apparently promising achievements than a rigorous guidance to actual technique. Plus, the clash between new "vocabulary" and freedom in molding forms, especially if we consider the neighborhood scale, reveals the subjectivity of constraints. Selection (and quantification) of parameters, hierarchy of geometric operations and performance criteria should all be responsible choices of human elements, choices that have highly deterministic effects on outcome morphology. Such responsibility is extremely amplified, because the complex equilibria we encounter in planning composition go far beyond the constraints applied to engineering, product design and, to some extent, to architectural objects. Our perspective deals with higher complexity of forms and, above all, with multiple objects to be preserved in their individual, *specific qualities*.

In this perspective, our proposal would consist in moving from the *generic quality* of design to approach *specific quality*, empowering the chance to explore gradients as a support system that would possibly enable real applications to informed and efficient design, based on the substantial increase of realism in managing the complexity of urban form. This perspective points to leverage custom or "user-defined" constraints that, as we will see through the evolution of parametrics, prove to be possible with *digital* tools rather than *analog* experiences. These constraint systems would need to consider the respective impacts of horizontal and vertical occupation together with the adaptation of instructive load, so that this proves to be proportionate to the level of complexity imposed by such goal of realism through specific quality.

At the same time, it is vital, at least for the sake of intellectual honesty, to acknowledge the boundaries of this proposal, from the point of view of both underlying assumptions and operational drawbacks. On the one hand, we should deal with the inevitable partiality of our premises, since the stream of considerations that led us to a proposal of integration closely relates to a restricted selection of case studies. As a matter of fact, our proposal owes a cultural debt to a rather narrow range of references, which makes it something that should be appreciated as a starting point for further development and certainly not as a "universalistic" or "revolutionary" step forward to some sort of automated and "ready-made" design.

In other words, our parametric model is not a complete response to generic quality for real urban design practice, due to a number of compromises with (and resistances of) a tool that was originally developed for architects. This being the case, it may yet be considered as a first step, waiting for further rethinking and adaptation to sharper challenges of geometry. Our example looks more after a "tester" that, given its own limits and rooms for sophistication, supports advising and relating occupation patterns with a real-time (or *responsive*) evaluation of morphological performance. This will contemplate *solar density* and *compactness* levels with respect to energy, and, as an integration, three complementary measures of efficiency that typically "push" for specific regimes of occupation, having in turn their impact on energy measures. These will be *natural surveillance* of streets (acting as an horizontal factor of occupation), *diversity* of heights (acting as a vertical factor of occupation) and open space compression or *spaciousness* (acting as both horizontal and vertical factor of occupation). Given such premises, this test-bed model would already boast better approximation compared to the case studies selected for this work, but still, it would confirm an inevitable gap from design reality, where we necessarily deal with ever more complex distortions and larger amounts of variables to be kept an eye on.

But this parametric exercise would also be an occasion of learning and experiencing that middle land between theory and practice, going beyond the rhetoric that currently overworks theoretical discussions upon the supposedly endless opportunities of parametrics. This would serve to acquire, instead, a gradual awareness of both potentials and drawbacks of technique with respect to a certain degree of complexity, toward the urban design

scope. We refer, in particular, to some inertial elements spurring from the intrinsic and systematic vocabulary of parametric-algorithmic modeling in relation to our intentions as (human) city-makers.
The hypothesis of an integration for accurate appraisals of design quality, having its roots within a context of complex equilibria of composition, aims at considering the balance of solar capture together with its "intersection factors" through parametric manipulation of form, horizontally and vertically across shapes and densities. We should recognize that the reductive bias of our approach insists on dimensions considered as well, despite the battery of indicators *ut supra* includes measures that case studies tend to ignore along the process of morphogenesis. In fact, we miss other important economic and environmental dimensions; for instance, we dismiss open space comfort and the financial feasibility related to each volume change. However, these measures, once we provide the model with output form, could be integrated within a compound apparatus of evaluation afterwards. In parallel, surrounding context will be considered as a bordering obstruction of our parametric model, i.e. something whose presence will find justification only for neutralizing edge effects of solar analysis rather than promoting a bi-directional interaction with test-bed arrangements.
The early design stage may derive important benefits from a model able to match continuous "frames" of form with energy implications in a parametric tense, especially if we think that initial phases tend to imprint decisive or at least highly influential conditions on output performance in terms of energy efficiency (Nault et al., 2015). Contemporarily, this effort would insist on the same direction of increasing demands for certification warranty, such as what LEED has been releasing for conveying standards of excellence toward sustainable neighborhood scopes (Haapio, 2012).
Active and passive strategies for on-site renewables and energy-savvy intelligence both find predisposition of urban form as a necessary precondition, which surely qualifies a matter of harmony with nature, consciousness as transitory beings and investment in true civilization. However, such precondition represents a delicate point of equilibrium among different and sometimes contrasting forces acting on urban space, which strongly need to be balanced holistically. High-density land use promotes energy-saving opportunities up until certain thresholds, where we come to deal with a mutually interacting variety of constraints: basic requisites such as building regulations on the one hand, and socio-cultural praxes like visual control patterns of collective space, landscape and aesthetic strategies or even protection of the architectural heritage on the other. All these constraint forces impose limits on compositional freedom, reducing the room for direct storage of solar energy with the multiplication of shadow-casting obstructions and inappropriate surface orientations (Montavon, 2010).
According to this framework, the role of digital tools in producing urban space may prove to be a powerful aid to project development, trial-and-error and formalization. Besides, developing advanced tools for coordinating morphogenesis with simulation would be justified as investing in the validation of design assumptions would reduce risks of undesirable effects (Mueller, 2010). Parametric design may become an interesting contribution to such empowerment of planning tools, as it helps investigating compositional issues by unlocking the stream of combinations between data and rules, while providing insights not directly accessible to one-off standards of solution.

PART 1 THE THEORETICAL FRAMEWORK

Reproducing a sound theoretical framework for parametric design: the option of diagramming morphogenetic processes in search of performing outcomes

1.1. The evolving connotation of design practice through a central shift: from *traditional drawing* toward *parametric diagramming* techniques

1.1.1. Not just a digitalization of the drawing process, but a structural change in the modes of idea generation, design synthesis and human-machine interaction

Parametric design environments represent a step out of the mere conversion of drawing boards to a system of electronic canvases. As such, they restructure the inherent nature of interactions between human element and machine calculation starting from the roots of thought processes and stretching to their translation into design outcomes.

In this light, an important aspect is to recognize the *ontology* of design, something that underpins the process of conceiving spatial solutions by the simple act of *drawing*, which consists in choosing, drafting and organizing a set of graphical symbols in a tectonic arrangement of some consistency. Drawing is, indeed, the core medium through which architects and urban designers assemble a lexicon of traces to enable the exploration of formal layouts in a process of *design synthesis*. In one of his last articles, Robin Evans (1989) shortly, but plainly discriminates the sense of design from mere operational construction.

«Architects do not make buildings, they make drawings of buildings» (Evans, 1989, p. 369).

By extension, the same difference applies to urban design: what designers produce, aside from numerical operations, inevitably consists in drawings. Drawings have long been the privileged medium for not only organizing ideas, resources and space, but also supporting the prediction of design outcomes.

The advent of digital modeling tools has vividly contributed to the evolution of representations, sometimes leading to highly sophisticated styles but not to substantial methodological revolutions: CAD interfaces point at reproducing a digital skin for paper and drawing utensils that, in the end, trace signs on a computer canvas as if they were tools of a traditional drawing board. Even after perspective and projective geometry, which have characterized Renaissance and Modernism respectively, the set of instruments has not undergone any change in the way both analog and digital models translate human intentions.

In this case, each creative act still relies on a direct conversion of intentions into (analog or digital) drawings, whose status of architectural or urban "models" strictly depends on how human mind filters such drawings. In turn, the effective interpretation of models stems from a direct link between ideas of the intellect and signs of a geometric alphabet (Tedeschi, 2014). Drawing is, in brief, an instrumental gesture with an aim at operationalizing ideas by converting concepts into conventional signs[18]. As such, it can be considered as a *hand mold* that is responsible for a natural interaction between mind-rooted ideas and corresponding shapes.

[18] Which means symbols, patterns, colors and tracing styles, whose reliability lies in sharing unavoidable codifications of their meanings: the fall of a shared alphabet of signs would represent, in all likelihood, the slump of any chance for human interpretation. The sense of such concept of "convention" should not be confused with what Gabellini (1996; 2001) defines as *conventional representation* genre of planning: peaked with Modernism, conventional design represents the extreme conformity to a special and unambiguous library of graphic choices; however, our conceptualization, being far broader, may be applied as well to what the scholar defines as *iconic representation*. The substance does not stand as much in the outward style of design, but rather in its sound ontology: design as a simple trace on a paper (Tedeschi, 2014).

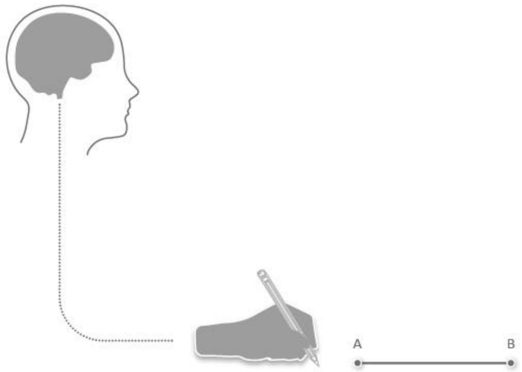

Fig. 13. The hand obeys the intellect, reproducing signs laden with conventional or mind-rooted meanings (elaboration from Tedeschi, 2014).

Recognizing the distinction between actual objects and representations is central to a sound understanding of methodological change with respect to parametric design. This introductory passage, although limited in size, stands as a decisive marker for the whole stream of following considerations, since the genesis of conceptual ideas as solvers of a particular design problem is a strong determinant for the resulting spatial qualities.

1.1.2. From an *additive* to an *associative* dynamic of the design process: the transfiguration of cognitive matter through the act of drawing and the materialization of form

Based on the considerations above, we can now appreciate how parametric systems reformulate the properties of drawing from an *ontological* perspective. The fundamental distinction between *traditional* and *parametric* modeling lies on the dynamic processes through which models come to be, in an effort to achieve the complex set of interdependencies that human mind can imagine[19]. In this respect, we can discern two kinds of processes: *additive* dynamic and *associative* dynamic. An *additive* dynamic describes the act of replicating complex interdependencies by means of traditional modeling. On the contrary, parametric modeling is the plain manifestation of an *associative* dynamic (Tedeschi, 2014).

Traditional drawing is *additive* because it consists in concretizing mind-rooted relationships by adding independent signs traced on paper or CAD worksheets. The result of an additive dynamic is, in essence, an overlapping array of self-contained compositional elements that do not contemplate any associative relation. The quest for *design synthesis* comes about in conformity to the sole "standard" or conventional meanings of representation codes, while both meaning and internal consistency of models are utterly entrusted to the designer (Tedeschi, 2014). This means that the medium itself does not guarantee the full embodiment of relationships that we can imagine through cognitive efforts. In other words, we use drawings instrumentally to "disguise" the inherently *associative* relationships of human mind as an overlap of conventional, isolated symbols. The property of traditional drawing confirms the fact that what we see on a paper is nothing more than a "*plan*", a "*sketch*" or a "*draft*": it can be interpreted as a building (or a group of buildings) through consolidate lexicon only. Although valuable in principle, the overall quality, beauty and fame of drawing examples (fig. X) are all aspects that do not count, as long as such drawings share an *additive* genesis from an *ontological* viewpoint.

[19] Since every act of design is extremely sensitive to relationships, this aspect becomes of primary importance within not only the architectural, but also the urban domain. Perhaps the very sense of each project draws its core value from how it relates the different, but complementary tiles it is made up of, understanding their potential as an aggregate and evocative figure.

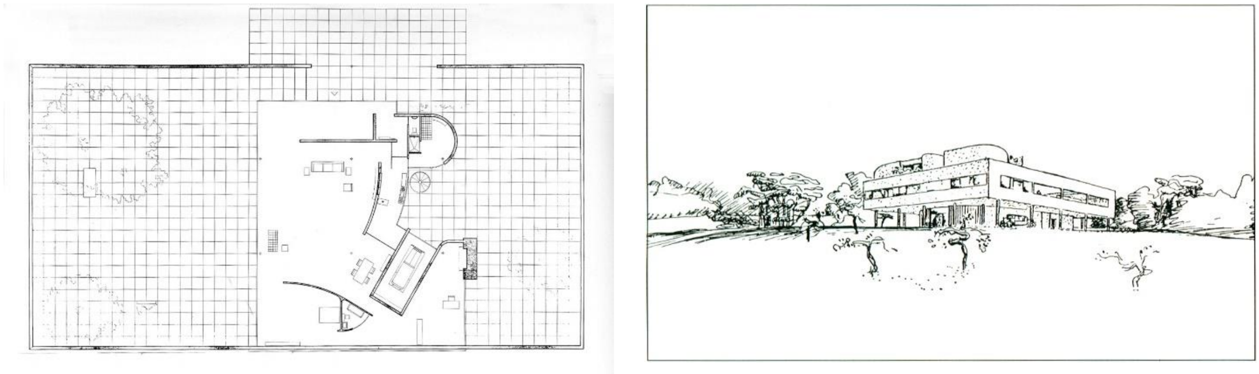

Fig. 14. On the left side: blueprint of the *House with a patio and garage* by Mies van der Rohe, 1934 (retrieved from http://drs-rdt.tumblr.com/). On the right side: sketch of *Villa Savoye* by Le Corbusier, 1931 (retrieved from http://cea-seminar.blogspot.it/).

As we already mentioned, additive dynamic implies that the act of drawing derails from cognitive mechanisms underpinning the creative process: typically, these mechanisms work by establishing interrelations rather than adding information. However, traditional drawing implies another limit, this time based on the structural qualities of represented objects. In fact, this kind of drawing process excludes the injection of constraints that are physically relevant for the generation of shapes, which multiplies the number of corrections along the series of overlapping layers over time. For example, additive processes do not comply with how forces such as gravity, wind and solar rays restrict deformations and displacements of form in *associative* ways (Tedeschi, 2014).
Both these limits have long forced designers to reiterate definitive tectonic systems by adding and rubbing out independent signs in periodic successions. This has been dramatizing the synthetic phase of design as a rigid process of testing and re-adjusting structural relationships rather than adapting those structures to given constraints across willowy grids.
Despite the digital conversion of this process, what CAD software has improved concerns the ability to perform repetitive tasks, with consistent savings in terms of timing and manual efforts, but with no true revolutions in the actual transposition of cognitive logics to tangible results. With this respect, CAD has been just a digitization of *additive* hand drawing, a prosthesis substituting the tools of analog drawing boards and entrusting the overall consistency of tectonic "phonology" to the human element. CAD layers may help defining hierarchies and interrelations, but still contain signs that are intrinsically independent from each other. In this case, the mouse is what substitutes the tool, namely pencils and nibs, but not the underlying logics of design: it performs as a simple extension of the brain, by simulating the "presence" of the hand in the *virtual* environment.

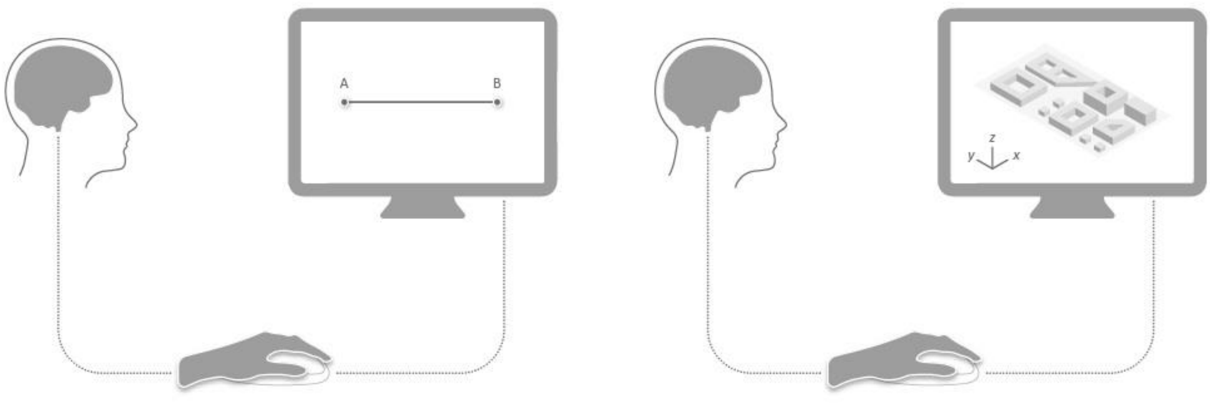

Fig. 15. Mouse, navigator and CAD toolbars are simply digital prostheses of traditional *additive* assembly (elaboration from Tedeschi, 2014).

In his attempt to systematize parametric knowledge, Woodbury (2010) introduces the new methodology in a similar way, as something going beyond the emulation of a conventional *modus operandi*, where "adding" and "subtracting" are the only design moves available for designers to achieve complexity on the paper.

> *«The archetypal design medium is pencil and paper. More precisely: pencil, eraser and paper. The pencil adds and the eraser subtracts. Add a few tools, like a T-square, triangle, compass and scale, and drawings can become accurate and precise models of a design idea. Designers are used to working in this mode. Add marks and take them away, with conventions for relating marks together»* (Woodbury, 2010, p. 11).

Parametric modelling allows designers to overcome the limits of an *additive* dynamic by getting closer to the *associative* nature of both design intents and structural properties. Due to a system of constraints, the model is not anymore an array of independent signs, but it performs as a "living" substance as its parts relate and change together in a coordinated way[20] (Woodbury, 2010). In this new *associative* light, a coordinated change is what verifies both meaning and structural coherence of spatial arrangements, which are now entrusted to the model itself.
An *associative* dynamic implies the expansion of design options beyond the simple operations of addition and erasure: designers can now *add*, *erase*, *relate* and *repair* (Woodbury, 2010). In particular, r*elating* and *repairing* describe a fundamental change in modeling workflows and design checking. The act of *relating* requires explicit reflections about the kind of relations to opt for. For instance, at a certain point of the workflow, designers may demand that a series of points lie *along* or *near* a specific line. *Repairing* is another important result of *associative* systems of dependencies: it occurs after an erasure, when the parts that depend on an erased part restore relationships with the parts that remain, granting the elastic "coagulation" of the model.

1.1.3. Intersecting the two dynamics of the design process through the lens of morphological manipulation: from *form-making* to a *form-finding* approach

Additive and *associative* dynamics entertain a close nexus with the epiphany of morphological solutions during *design synthesis* processes. In this perspective, we can highlight an important theoretical distinction between two approaches: *form-making* and *form-finding* (Tedeschi, 2014).
The use of traditional drawings, despite their inherent limitations, has acquired the status of a relatively stable technique within the fields of architecture and urban design over the centuries. *Form-making* is what has been characterizing the process of shaping spatial environments through the diffused consolidation of *additive* dynamics. This approach has been coupling conventional libraries of symbols with a strong reliance on codified typologies. By typologies, we mean well-proven, preconceived solutions that need to be accurately integrated into tectonic systems, due to their intrinsic nature of pure, ideal-type forms. As such, *form-making* appreciates the gradual combination of given types, which typically populate more or less renowned literary and technical manuals, based on a predefined set of formal and structural constraints. Besides, the term "*making*" sharply expresses an emphasis on the unceasing, quibbling fabrication of variants needed to achieve refined relational qualities.
The development of parametric systems has made possible to complement *form-making* with a newborn and promising paradigm, namely form-finding. This approach underlines the stimulation of creativity and human interpretation with a sense of "emergent unexpectedness" that cannot be forcedly reproduced through preconceived refinements of conventional drawing[21].

[20] Due to the *associative* bounds of constraint expressions, which stand as overarching rules for the production of formal solutions.
[21] However, this definition does not necessarily imply that parametric systems and *form-making* practice are incompatible sides, since parametric editing leaves room for flexible reproductions of *form-making* assembly as well.

In fact, *form-finding* approaches imply the genuine discovery of novel shapes through either *scrolling* the inputs of a parametric system or closing them in an *optimization* cycle, given precise conditional expressions. Going beyond the capabilities of human mind, parametric optimization techniques necessarily yield unpredicted results, at least within a context where materials, shapes and structures describe complex *associative* relationships (Tedeschi, 2014). *Optimization* is a rather promising, yet long-lived concept in parametric modeling. Actually, its close connections with *form-finding* practice emerged at the earliest stages of parametric design history, more specifically in the late 19th century, as an integral part of the methodology. For example, pioneers of parametric modeling such as Gaudí (1852-1926), Isler (1926-2009), Otto (1925-) and Musmeci (1926-1981) have rejected predefined typologies, in an attempt to look into the rules of self-formation processes in nature as inspirations for organizing original building structures. Since these arrangements could not descend from empirically grounded solutions, conventional drawing could not be used anymore as a tool to predict design outcomes (Tedeschi, 2014). In their attempt to examine the spontaneous behavior of form, the first *form-finding* pioneers replaced traditional drawing with analog devices that leveraged physical principles as a morphogenetic "pool"[22], showing how dynamic forces could mold self-optimized architectural forms. More recently, the increasing complexity of building structures has given *form-finding* strategies a conspicuous importance, since this practice helps in determining the shapes that respond to indeterminate structural demands[23].
Originally, structural optimization processes through physical *associative* prototypes was *mono-parametric*, i.e. grounded on the contribution of forces taken singularly. *Gravity* has been central to the development of such researches with this respect (Davis, 2013; Tedeschi, 2014). Studies that are more recent have begun to look into shape generation against *multi-parametric form-finding*. The aim consists in embodying diverse datasets within a single "gene pool", which comprises geometry as well as dynamic forces, climate and even social composition (Tedeschi, 2014).

1.1.4. The foundational aspects of "*parametric thinking*" and the attention to structural-relational quality: drawing massing solutions vs. drawing *diagrams* of massing solutions

The third point of an essay written by Bruce Mau, the *Incomplete Manifesto for Growth* (1998), directly reflects an important concept of parametric design, with respect to a process-based perspective.

> *«Process is more important than outcome. When the outcome drives the process, we will only ever go to where we have already been. If process drives outcome we may not know where we are going, but we will know we want to be there»* (Mau, 1998).

We know that the underlying rationale of parametric design allows designers to find variable solutions that go beyond the limitations of static (and *additive*) CAD software and 3D modelers. As *associative* dynamics constitute well-defined sets of morphogenetic guidelines, outcomes become only the outward image of an instructive process that insists on established parameters and relationships, and not on a preconceived appearance. "*Parametric thinking*" means formulating thought processes around this awareness, recognizing variation and correlation mechanisms as driving conditions for the emergence of specific forms (Woodbury, 2010).
More generally, parametric thinking represents an aptitude to establish relationships among properties within a system, namely a design proposal, independently from the technical characteristics of digital tools (Karle & Kelly, 2011). This implies a delicate effort in altering the logics of consolidate workflows: for example, the way in which design is conceived, represented, and fabricated is likely to be affected, since the outcome rises from

[22] Some examples include physical models such as soap films that found minimal surfaces, suspended fabric that found compression-only vaults and branched structures (Tedeschi, 2014; Woodbury, 2010).
[23] An example of indeterminate demands may be achieving the minimization of land occupation, by keeping constant the desired measures of compactness, such as virtuous "benchmark values" for a volume-to-surface index.

design parameters and not anymore from pre-packaged solutions, however documented these may be[24]. Independently from recent achievements in computing, which have certainly contributed to the sophistication of a constraint-based approach, the "upside-down" logics of parametric thinking entail that users need to define variables first, in accordance with relevant design questions[25] (Karle & Kelly, 2011).

The apparatus of *associative* rules that constitute a *parametric diagram* can be expressed through a conceptual representation based on *graph* structures. Over the last decades, these conceptual models have been considered as worth to be emulated by software interfaces due to their intuitive grammar of relationships, leading to *visual* forms of instructive rules. A general property is that the intricacy of parametric diagrams mirrors the complexity of rulesets. In particular, the organizational complexity of *form-finding* results depends on both entity and configuration of their *associative* skeletons. Through the diagram, the associations describe a construction process that blends parametric primitives into more and more complex objects. A basic example can be a process in which a line stems from connecting two point geometries, a square from connecting four lines, etc. By construction, these graph structures sustain a combinatorial bundle of incremental associations, where:

> *«[…] any conceivable network of relations between a given set of element attributes can be constructed»* (Schumacher, 2010, p. 353).

1.1.4.2. *Thinking with abstraction: skimming geometry toward malleable and transient matter*

A consistent slice of parametric thinking requires the acknowledgement that every design element in the model can be revisited as a *node* of a parametric *graph*. This interpretation suggests that *concrete* objects such as walls and floors of a particular size back out of predetermined layouts, in return for "glowing" properties that reside in the *abstraction* of substance. The term "abstraction" is a laden word, thus it calls for immediate clarifications. In fact, the same concept can be used differently, according to both the context of discussion and the human profiles involved (Woodbury, 2010). For example, its use tends to differ even between two key figures of parametric knowledge, designers and computer scientists. We can state that an abstraction describes a general concept rather than a specific example. But this definition is still sensitive to the accustomed lenses of lay people and professionals.

In common language, abstraction is typically associated with "vagueness", hinting that inferring much from an abstract idea may be hard work. In design and computing technology, the word acquires two different undertones that are not mutually exclusive. Design appreciates the *protean* nature of abstract concepts: malleability is always a well-liked quality of ideas, since it provides a stable base from which many alternatives can be flexibly generated. In other words, an abstract concept can be realized in diverse and adaptable ways, or can be given many interpretations, each of which may have numerous concretizations (Woodbury, 2010). Computer scientists give the term "abstraction" the meaning of a process through which several instances are attributed to a class by leaving out inessential detail: the quality computer scientists appreciate is, in this case, codification, which grants enough formalism to permit manifold applications. Formalization confers computational ideas a status of generality that is highly desirable for mathematical experts, as it draws value from versatility of use.

[24] Anyway, this does not exclude the tentative introduction of standard solutions within a parametric model. In fact, the interpretation required for parametric thinking depicts such solutions as nothing more than inevitable results of conventional parametric inputs, which can also take place in the overall diagram as parameters depend on design intentions.

[25] Despite the implicit accordance with design objectives, this aspect comes at a cost, due to the inherently changing nature of judgement through the evolution of a design process. Davis (2013) argues that both technical and political judgement may consider, for instance, the need for substituting existing parametric dimensions or even adding new ones, leading to either conversion or complexification issues that rise from the "soldered" make of relational patterns among inputs and their transformation rules. With respect to urban design, we will consider this aspect as one of the emerging shortcomings of parametric modeling in the conclusive part of the work (see section 3.4.2).

Although usually familiar to scientific minds, this process of abstraction through codified characters is a practice common to designers too: dimensional modules, structural centerlines and standard details all are media for abstract design ideas (Woodbury, 2010).
In a parametric system, abstraction mates both meanings without implying any ascension towards conceptual conjectures along the ladder of detail. It consists, rather, in skimming geometry so that each of its observable configurations, although concretely defined, is simply the result of precise attribute settings. As such, it becomes a "living" matter, whose behavior changes according to virtually endless permutations of inputs.

> *«The final output is not just a "digital sign", but it can be considered as an interactive […] model responding to variations in the input by manipulating the entire system»* (Tedeschi, 2014, p. 24).

Converting concrete geometry instances into abstract nodes makes the overall parametric model applicable to different situations, because it would depend only on essential inputs without any binding reference to specific details. Abstracting geometry means adopting a new lens, a discerning membrane through which single objects lose their solid dress to become a transient snapshot, open to diverse possibilities for reuse. The renowned poet William Blake (1757-1827) would have known how to express the "unlocking" opportunities of parameterization by means of few, but effective words:

> *«If the doors of perception were cleansed, everything would appear to man as it is: infinite»* (William Blake).

Since time for designing is always in short supply, skimming geometry becomes a strategic feature of parametric design. Woodbury (2010, p. 30) suggests that well-crafted abstractions are a key part of efficient modelling. This is because much modelling work tends to assume similar patterns: as such, it would benefit from the reuse of parts of one model into another.
Let us take a simple floor plan with rectangular rooms as an example (Woodbury, 2010, p. 31). In this case, we can translate walls into nodes of a parametric diagram to unlock their variation intervals. Using the entities of walls as nodes (*fig.* X), we obtain a tree structure in which vertical (*v*) and horizontal (*h*) wall-nodes inform the configuration of each room across a simple chain of relationships. Walls and, by consequence, their in-between room spaces do not represent a *drained* image of perception any longer: rather, they only reproduce a transitory concretion of *liquid* data stocks: each node stores sensitive information, acting as a matrix of visible outcomes. In particular, walls (or, better, what we *see* as walls) store info about their location, sliding through a bidimensional domain, and defining room size data accordingly[26].

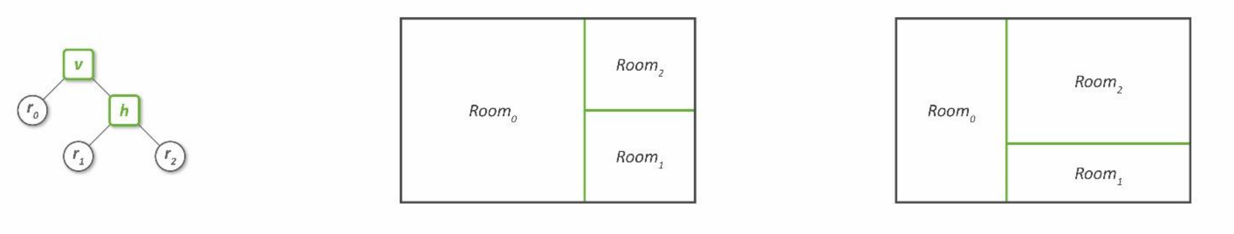

Fig. 16. The basic tree structure on the left represents an abstraction matrix of what we are accustomed to see as a floor plan. At the center, we find one possible concrete outcome, which can be "liquidly" changed as either or both wall data (the location with respect to a coordinate system) slide through their domain (within a fixed apartment size), averting the final layout (elaboration from Woodbury, 2010).

[26] Which means, following the *associative* logic of geometries.

Following the same abstraction practice, the tree structure may accommodate recursive dissections, which can divide the plan in either vertical or horizontal directions, depending on diagram-based relational qualities and, of course, wall location data.

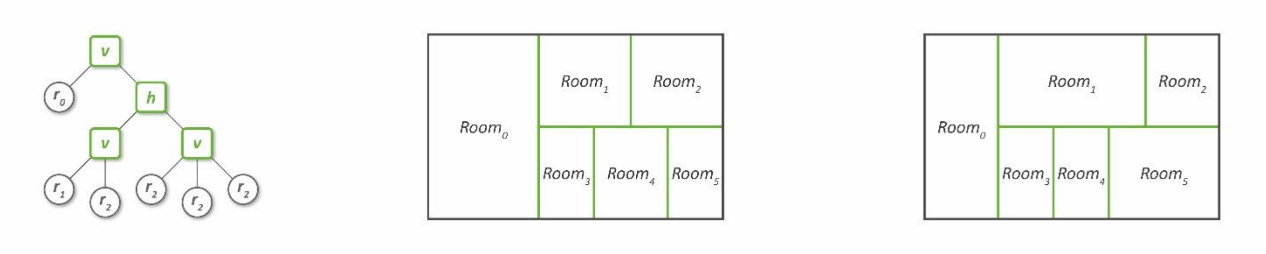

Fig. 17. Another possible diagram (on the left), whose dendritic expansion responds to a purpose of recursive dissections. We can see in the center one outcome of such alteration at a structural level. Besides, we can modify parametric inputs for walls once more, altering the dimensions of rooms without compromising dissection principles (on the right) (elaboration from Woodbury, 2010).

As a corollary to our previous considerations, we can appreciate the opportunity of *condensing* and *expanding* graph nodes as a relevant consequence of parametric abstraction. A collection of nodes can be condensed into a single node; in turn, each condensed node can be expanded to restore the graph to its original image. Graphs with condensed nodes are called *compound graphs* (Woodbury, 2010). For convenience, the options of condensing and expanding groups of nodes can be implemented whenever designers need to transfer one or more stocks of relational patterns from a design environment to the other.

1.1.4.3. *Overcoming constraints: diagramming with the use of specific formal quality conditions*

The arrangement settings of both *nodes* and *links* in a parametric graph describes an integrated set of *constraint* expressions. *Constraints* represent formal quality conditions as *associative* bonds, whose role consists in regulating the transfer of input information, namely a configuration of parametric values, toward specific outcome physiognomies. In this sense, the overall diagram can be considered as a mechanism that divides the condition imposed by such settings into easily solvable intermediate problems, recomposing the answers into a complete solution (Woodbury, 2010).

Constraints act as pillar factors of the general systems of rules at the base of behavioral determination in *form-finding* practice. Within architectural and urban design fields, these rulesets can consist in planning measures, site restrictions, exposure, views or floor-to-floor heights. Organizing the parametric diagram as a network of behavioral codes for morphology emphasizes the idea of an "emergent" layout denying any preconceived notion. As pivotal engines of a parametric assembly, constraints give a finalization sense to input variables, enabling the control of design proposals within the formal conditions they impose to constituent elements. This "part-to-whole" approach is the natural consequence of *associative* logics, which characterize any parametric variation: the behavior at each elementary level always results in the alteration of the aggregate level (Karle & Kelly, 2011).

Parametric thinking with respect to constraint-based modeling frames projects as derived from both parameters and rulesets. This implicates the gravitation of responsibility from the reproduction of a "right design" to the negotiation of "right questions", which greatly influence the morphogenetic process as they determine both input choices and behavioral patterns (Karle & Kelly, 2011).

1.1.4.1. *Conceiving data flow: the sense of graphs as figurative tools for diagram representation*

The *links* of a parametric graph support the *associative* system of relationships among abstract *nodes*, concurring to a conditioned sequence of constraints. Together with abstraction processes and constraint-based modeling, focusing on the connective pattern of design elements is another pertinent aspect of parametric diagramming, which unveils origin, direction and incidence of input flows across the graph.
Connections in a parametric diagram organize the flow of input data so that it goes through a definite array of constraint expressions, gathering their midway outputs to compose the final one as a solving picture. The arrangement of nodes, with inputs at the beginning of the "*data tree*" and constraints ordered to define morphogenetic vessels, inevitably depicts a *directed* graph (Woodbury, 2010). As designers alter one or more values of input settings, the linkage system channels information updates across the same series of constraints, leading to the automatic adaptation of outputs.
Thus, the way in which data flows through the diagram deeply affects both the possible designs and the interaction with the human element. Of course, the incidence of these self-adjusting "echoes" upon the overall diagram may vary depending on how many input data submit to change: this characteristic grants users a determining role despite the spontaneous reverberation of the model.
Moreover, no single ruleset disciplines the process until the user gives explicit authority to one over the other. The structure of data flows helps discerning the dependency patterns of graph nodes, which is proportionate to the level of *associative* integration performed by the outcome (Karle & Kelly, 2011). Its direction moves from independent to dependent nodes, such that known information is upstream of unknown information. In other words, the system *propagates* from knowns to compute the unknowns (Woodbury, 2010).
We can illustrate the conception of data flow with the example of the three-room rectangular plan that we have already encountered in the previous pages. Focusing on room sizes, the example demonstrates that parametric diagrams can assume different configurations, having from slight to consistent impacts on relational behaviors. Being *w* nodes the widths and *h* nodes the heights referred to each room and the floor plan as a whole, the tree of dependencies depicts diverse deformation patterns for the outcome apartment, as modifications take control of parameters at the source of propagation channels. In *figure* X, we point out three versions of a graph-based parametric diagram starting from a "base scenario", so that we come to appreciate dissimilarities with respect to propagation patterns.
In case **A**, the diagram is arranged in such a way that the width of $room_0$ and the whole plan are the root parameters of the system, as well as the overall height and the height of $room_1$, while the width of $room_1$ strictly constricts the one of $room_2$. We highlight two hypothetical variations of root parameters. Suppose, for example, to reduce the width of $room_0$ and increase the height of $room_1$ at once: in this case, $room_1$ takes over additional space in both dimensions; in parallel, $room_2$ follows the width of $room_1$, losing ground in terms of height.
Suppose now to restart from the same base scenario, choosing to expand both width and height of the overall plan: here we should not expect $room_0$ to respond with an automatic expansion of its width, since the latter is totally independent from any change. Rather, the expansion would affect the width of $room_1$, which, in turn, influences the width of $room_2$. $Room_2$ varies elastically along both dimensions, while $room_0$ only reacts to the overall increase in height.
In case **B**, we assist to slight changes in the "*relational field*"[27] of rooms: for example, now $room_1$ is bound to be a perfect square, due to the direct dependency of its height from its own width. At the same time, the width of $room_0$ becomes a consequence of what can be set for the width of either or both $room_1$ and the overall plan. If we reduce the width of $room_1$, $room_0$ acquires part of both $room_1$ and $room_2$ in terms of width, since the width of $room_2$ varies according to the width of $room_1$ as in the case before. Nonetheless, $room_2$ takes over the space once occupied by $room_1$ in terms of height, due to the square proportion of the latter and the constant settings of the plan as a whole.

[27] A term extensively used in Schumacher (2010).

If we opt for expanding the width of $room_1$ and both dimensions of the plan, we observe a proportionate expansion of room1. $Room_2$ loses ground to $room_1$, but it assumes its increment of width and the overall increase in height of the plan; contemporarily, $room_0$ loses ground to $room_1$, but it also responds to the overall increase in width of the apartment.

In case **C**, we assist to the assembly of another system of constraints, which happens to be a specification of the previous case: $room_1$ is still a square, but its width is proportional to the overall width of the plan. Here we see two patterns of variation-correlation of the system. First, we suppose to increase only the width of the aggregate plan. Such variation is particularly interesting with reference to parametric dependencies, because it automatically triggers a multiple *propagation effect*. $Room_1$ expands according to the same coefficient of proportionality (*a*); as it maintains a squared shape, it also increases its height, but with no proportionality to the overall height of the apartment. $Room_2$ loses part of its space along the vertical dimension, but it behaves as $room_1$ horizontally. $Room_0$ loses space to both $room_1$ and $room_2$; eventually, its horizontal "payoff" describes an expansion, since it depends on the increase of the aggregate width as a whole. Finally, we may hypothesize a decrease of *a* and the parallel increase of the overall height. With a decrease of the coefficient, we do not observe alterations for the overall width, as *a* stands for an arbitrary ratio constricting $room_1$ only. However, the new constant also reduces the width of $room_2$, due to the particular configuration of our diagram. This means that $room_0$ expands both vertically and horizontally, while $room_2$, despite getting narrower in terms of width, adapts elastically to both the bound decrease of $room_1$ and the vertical increase of the apartment as a whole.

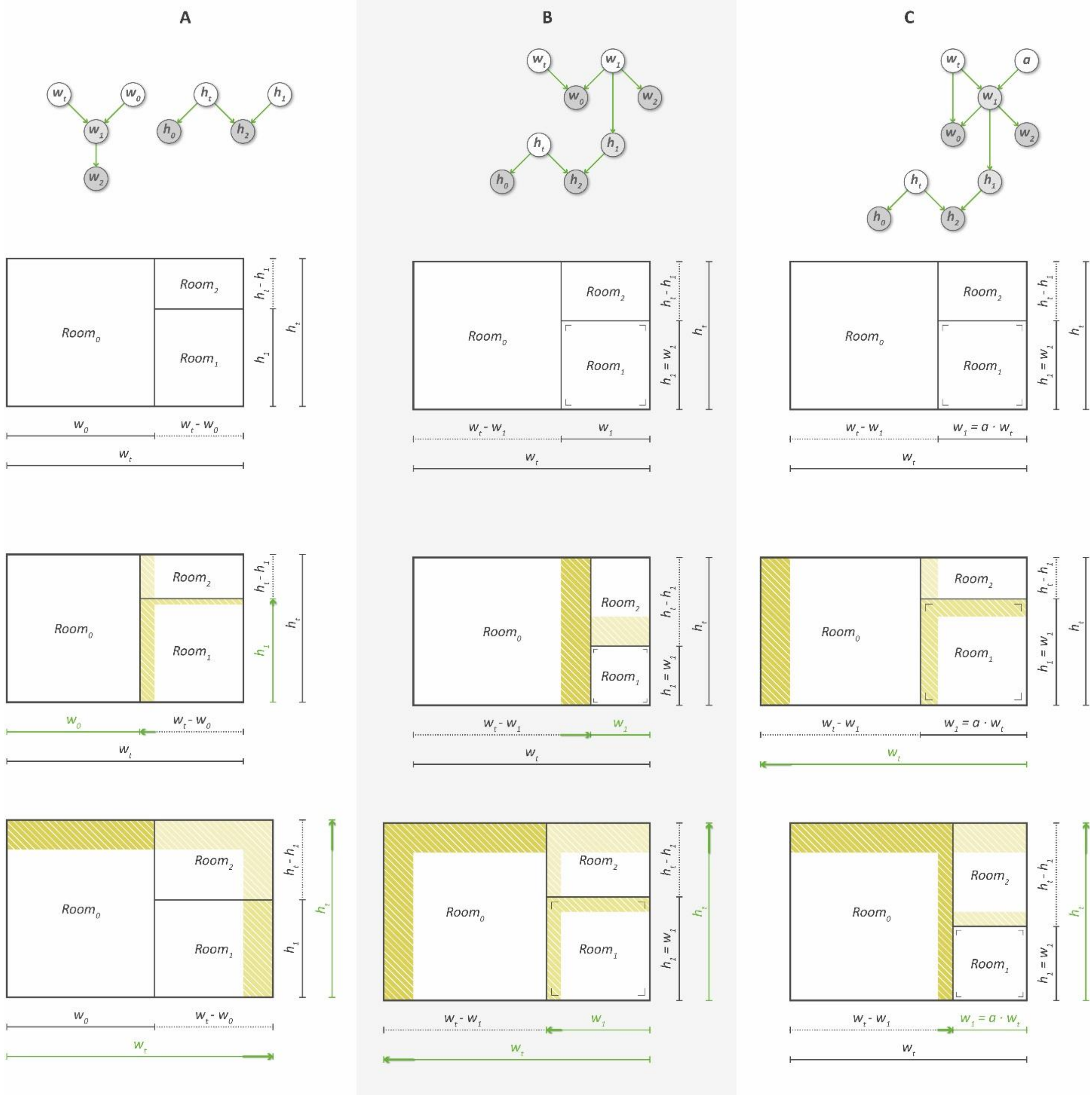

Fig. 18. Three different parametric diagrams, yielding different propagation effects, whose direction reflects the layout of arrows; within each diagram, we can distinguish gradual levels of dependency, from independent parameters (white) to ever more dependent geometric data (grey tones) (elaboration from Woodbury, 2010).

1.2. The instrumental use of *generative algorithms-aided* modelling as a practical operationalization of the *parametric diagramming* concept

Parametric design rises from a strong linkage between geometric manipulation and algorithmic modeling. In our perspective, these two approaches can be considered as close relatives able to leverage their complementary qualities in a self-powered liaison.
Controlling geometries represents the inventive means through which designers give shape to conceptual intentions by responding to a particular need. This practice, which meets the most impeding constraints especially when we handle complex surface systems such as settlement forms, may even come up with questioning intentions themselves, leading to perpetually reframed scopes, modalities and solutions. In contrast with a more traditional approach, parametric design proposes to place objectives first, in order to compare differing formal alternatives that always satisfy the gridded paths of an in-built *function* of performance. Constructing algorithms can be interpreted as the practical activity of producing such grids. Leveraging computational speed as a fertile test-bed opportunity for intricate models, algorithms act as tools that operationalize a diagram-led emergence of forms, which is central to parametric design experience, by channeling geometries through a defined series of treatment measures.
In this sense, the role of algorithmic modeling does not drain away with the mere automatization of design: this aspect is, in fact, just a superficial side of the practice, even though certainly comfortable, as some enthusiasts would argue (Schumacher, 2010). As a far more important aspect, the way in which such series of geometric operations is assembled in the algorithm defines the content of performance objectives in a tangible and verifiable way, charging *associative* bonds with a precise, user-defined rationale.

1.2.1. "*Algorithmic thinking*" for parametric manipulations of geometry: the definition of *algorithm* as a tool for managing the complexity of morphologies

Algorithms can be seen as foundational programs for morphological epiphany. In turn, such programs are written in accurate *programming languages*. In parametric design, it is essential that designers learn to "think algorithmically" by learning a programming language to accomplish design work (Woodbury, 2010). Anyone who has become a good programmer has focused intensely on programming to pick up tips and tricks of this methodology. The term "*language*" itself gives a hint about why this is so. Just as the most effective way to learn a natural language is to immerse oneself in the daily life of its native speakers, the best way to learn programming is working acutely with its syntax to the near exclusion of other forms of thought, which comes at a cost, as we will see among the *drawbacks* of parametric modelling[28].
Algorithmic programming is generally taught as an isolated skill, but, in the case of parametric design, it permeates an "*augmented keyboard*" of volumetric arrangements (cf. Brenna, 2004), by disguising the syntax of parametric diagrams as a proxy for editing the intimate *genetic code* of urban and architectural form. Rising above the particulars of a language is thus an essential step to see the more general, powerful concept at play.
We have seen that a parametric design, from an abstract point of view, can be represented as a *graph* in which every node contains a *constraint* expression. Punctuating a workflow with a series of constraint expressions can already be considered as an *algorithm*. The term "*algorithm*"[29] designates a procedure used to return a solution to a question, or to perform a particular task, through a finite list of well-defined commands (Tedeschi, 2014). Users can change an algorithm, at least in principle: in truth, the evolution of parametric design practice has moved from ancestral and *nature-based* algorithms, disciplined by either physical or chemical forces, to *user-defined* systems of rules. Long practice in using, programming and teaching parametric systems has shown that, eventually, designers will need (or want) to write their own algorithms backed by computer systems, in

[28] *Parametric drawbacks* will be discussed in depth in chapter X.
[29] Algorithms are named after the 9th century Persian mathematician Al-Khwarizmi (retrieved from http://www.etimo.it/).

order to make their intended designs (Woodbury, 2010). Among the several definitions of algorithm, Berlinski (1999) writes that:

> *«An algorithm is a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps, 1, 2, 3, …, whose execution requires no insight, cleverness, intuition, intelligence or perspicuity, and that, sooner or later, comes to an end»* (Berlinski, 1999, p. XIX).

Even though Berlinski's definition is less formal than those we can find in computer science texts, it contains the essential elements we need to describe algorithmic modeling. We can highlight two main aspects surging from such definition. The first is *procedure*: an algorithm describes a process that needs to be specified step-by-step. This is in line with the fundamental concept of diagramming architectural forms instead of representing standard solutions. Parametric design is not focused on *outcome* more than it is on the *process*, codified by a graph-based structure, through which a model comes to be: it means editing the *ontology* itself of design, although designers have been largely describing "final" objects rather than "in-between", but determining processes. The second aspect is *precision*: one misplaced character means that an algorithm likely will not work, i.e. will not produce any considerable result. As we will see more in detail in the next section by dealing with algorithmic properties, a necessary condition is that procedural instructions are written with no ambiguities, which means in conformity with the grammars of a particular programming language. Parametric modeling can only rely on what we will simply call from now on "working algorithms", those that prove to be immune to both syntactic and logical fallacies. In contrast, designerly representations, notwithstanding the memorable history of traditional drawing, are replete with imprecision, because they require human readers to interpret *additive* marks in appropriate (read *unambiguous*) ways (Woodbury, 2010).

1.2.2. The basic properties of algorithmic modelling: the *unambiguity* of instructions, the *definition* of the input and the *uniqueness* of the output

Algorithms follow the human aptitude to split a problem into a set of simple steps that can be easily computed (Tedeschi, 2014). In this sense, they are the natural operationalization of a parametric diagram in which every node stands for an in-between *constraint* to be locally overpassed and globally absorbed for the sake of a final, synthetic solution. Although they are strongly associated with computing technology, algorithms could be defined independently from programming languages[30]. As an example, a recipe can be considered as something similar to an algorithmic procedure. We can set a workflow for cooking a chocolate cake, based on a simple list of instructions: *1*) mix the ingredients; *2*) spread in a pan; *3*) bake in the oven; *4*) remove from the oven; *5*) cool in the fridge. Nevertheless, such a procedure cannot be fully considered an algorithm. In fact, the instructions we have here are far from being defined with no risk of ambiguity: we know we have to "mix the ingredients", but we completely ignore which ingredients we should use. How long should the cake cook? At what temperature? Unsurprisingly, lack of sufficient information is a common quirk of malfunctioning algorithms. This basic example points out some important categorical *properties* of algorithms, which can be distinguished into three general characteristics (Tedeschi, 2014): *unambiguity* of instructions (**a**), *definition* of the input (**b**) and *uniqueness* of the output (**c**).
An algorithm is an unambiguous set of properly defined instructions – An algorithm depends on user-defined instructions. This means that a result will be incorrect if the algorithm is not properly defined. Following the example *ut supra*, if steps in the recipe of a cake are inverted or skipped, the chances of a successful cake are likely to diminish. In other words, the more we define steps with sufficient (*input*) information, the sharper

[30] This is particularly the case of *analog* parametric methods, in which natural forces such as Newtonian mechanics and chemical reactions act as accurate rules for *associative* physical maquettes, as witnessed through works by Antoni Gaudí in the late XIX century and, more recently, by Frei Otto a century later (Davis, 2013). We will see in detail the nature of these studies in chapter 2.1 before briefly reviewing *digital* parametric tools.

will be the significance of the (*output*) result. As a core characteristic of parametric modeling, a meaningful sensitivity of outputs to the set of input data lies above all on a correct algorithmic syntax, which reflects the level of *associative* coherence among the parts of a design.
An algorithm expects a defined set of input – Input can be different for format and quantity. In our simple culinary example, step (*1*) requires ingredients; step (*2*) requires quantitative information such as baking temperature and time. Moreover, each input has a precondition, i.e. a requirement that must be met, such as a range of baking temperatures: for instance, not less than 160°C and no more than 200°C. We can refer to it as a mathematical or logical range or domain.
An algorithm generates a well-defined output – Given precise values and operations for input parameters and processing instructions respectively, the algorithm will always produce one exclusive output as a deterministic consequence of such specific settings. This means that, leaving both input parameters and processing instructions completely unchanged, the algorithm will generate the same result[31] independently from how many iterative launches it may undergo[32].

Fig. 19. A schematic representation of an algorithm (elaboration from Tedeschi, 2014).

Just as an ambiguous recipe is likely to produce an inedible cake, an algorithm whose grammar preconditions are not met can produce warnings or even error messages within the specific editor (Tedeschi, 2014). For instance, if we input numbers instead of a text and the format supported by input slots is firmly text-based, the algorithm will return an error[33].
Although we can conceptualize algorithms abstractly, as we will notice with the use of rule-based design as a feature common to both *analog* and *digital* parametric modeling, these tools tend to leverage the potential of computing technologies, which mainly consists in the capacity to rapidly perform tasks according to a given set of instructions. We should consider, however, that the kinship links between *analog* and *digital* families of parametric design take root in the procedural philosophy of algorithms by crossing over last century's computing revolutions. An example of this can be Newtonian laws in the physical models by Antoni Gaudí[34]. In fact, their interpretation as unambiguous, natural and real-time instructions for changing input measures still holds, leading to self-reconfiguring structures that always adapt final geometries accordingly, just as if they were described by a computer-based system of constraints.

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[31] Within our urban design scope, the algorithm would produce the same morphological layout in its 3D reference system.
[32] The independence of an intact algorithmic structure from iteration cycles represents a rather crucial principle, since it announces a fundamental distinction between algorithms that can be constructed in a *parametric* modeling environment and a purely *generative*, *evolutionary* and *optimizing* class of algorithms. This latter class is defined by a specific character of "self-adjustment" over series of cycles, which expands the process to a dynamic reproduction of outcomes rather than sticking accurately to a static one. However, the notion of *uniqueness* still holds even in the case of *evolutionary* algorithms, since each of their cycles ends with a temporary, but exclusive form of output. The distinction between these two types of algorithms will be explored in detail in chapter X, after the recognition of parametric design's *generative* roots.
[33] Syntax errors are common to computer environments in which automatic sessions of data treatment require properly formatted input as a necessary condition. We can think, in this case, to how much time is needed to construct rigorous database resources, so that the "eyes" of *Geographic Information Systems*, tools endorsed by much of planning activity all over the world, read the whole set of records with no impeding glitches (Paolillo, 2010; Migliaccio, 2008).
[34] We will unveil the essence of Gaudí's approaches in chapter X as one of the declinations of *analogue parametric design*.

1.2.4. The practice of *scripting* at the core of a procedural construction of geometries: the *visual programming* environment and the incremental assembly of *node diagrams*

In order to highlight the use of algorithmic modeling for purposes of parametric design, we can first recognize that algorithms consist of different classes (Tedeschi, 2014). A class that leads to a number is called a *computation procedure*, while an algorithm that generates a "yes or no" answer is called a *decision procedure*. In the specific case of parametric modeling, the *decision procedure* would be delegated to a human-driven debate, due to the inherently *unapophantic* nature of algorithmic outcomes[35]. Algorithms can also lead to 2D or 3D *geometries*. This latter category distinguishes parametric modeling processes as a particular sub-group of *computation procedures*.

The practice of executing algorithmic calculations in a computer environment implies typing instructions with the use of a specific *editor*. Editors can be *standalone* application or *embedded* in a software platform (Tedeschi, 2014). For example, *standalone* editors include programming languages such as *C#* and *Python*, while programs such as Rhinoceros and AutoCAD provide *embedded* editors, which allow users to write rules for automating tasks in more intuitive environments.

Speaking about *geometric computation* procedures within a three-dimensional coordinate system, if an *embedded editor* is used through modeling software such as CAD systems, a 3D geometry is created by either manipulating the standard set of primitives provided by the software or defining a procedural sequence of instructions (Tedeschi, 2014). For instance, a line can be defined by two points, a start and an end; points, in turn, can be defined by their coordinates {*x*, *y*, *z*}. Similarly, a vase model can be defined as the revolution of a profile curve around a vertical axis. More and more complex objects can be obtained by establishing a composite set of rules. We will see that this method can be carried out through a reasoned concatenation of mathematical or logical operators, depicting a step-by-step complexification of geometries.

In this perspective, such geometries are no longer manipulated with the manual movement of a mouse, but they are much rather defined by procedures expressed in a (correctly articulated) programming language. Examples can be *AutoLisp* in AutoCAD, *RhinoScript* in Rhinoceros, *MEL* in Maya and other cross-platform languages such as *Python*. Such an approach, usually referred to as *scripting*, is completely new for designers and reshapes the cognitive link between the idea and the final output. In particular, *scripting* consists of two working environments: **A**) the *editor*, and **B**) the 2D or 3D modeling *viewer* (*fig.* X).

[35] By "*unapophantic*" we strictly refer, in this case, to the Aristotelian conception of logical statements, formulated in one part of his *Organon* titled "De Interpretatione" (retrieved from: http://www.homolaicus.com/). *Unapophantic* judgements represent the negation of *apophantic* declarations; the term comes from the Greek ἀποφαντικός, "declarative, assertive", deriving, in turn, from ἀποφαίνω, "divulge, declare". Aristotle distinguished *apophantic* statements as descriptive, in contrast with evaluative, *unapophantic* judgements: according to the philosopher, the purpose of descriptions resides in showing something that can be verified as *true* or *false*, while evaluations relate to rhetoric, ethics and poetics, since they cannot be verified but in terms of partisan viewpoints, like *good* and *bad*. Every evaluation, even the ones pertaining to planning and design, is intrinsically and inexorably a *value* judgement, which responds to a partisan value system among the various possible ones (Fusco Girard & Nijkamp, 1997).

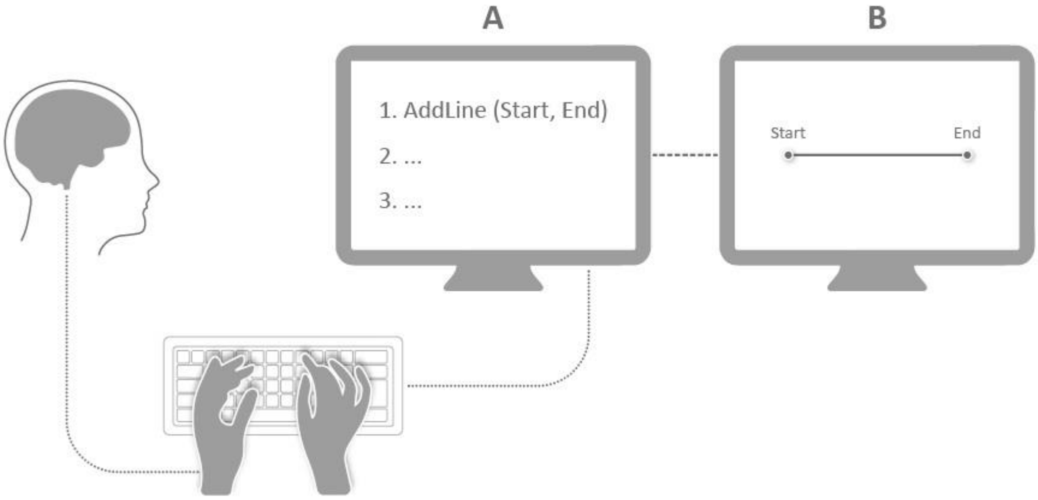

Fig. 20. Algorithmic modeling based on *scripting* consists of two main “windows”: the *editor* and the 2D or 3D modeling *viewer* (elaboration from Tedeschi, 2014).

Thus, an algorithm can be defined as the result of an act of *scripting*, whose output is constituted, in a parametric design realm, by *associative* 2D or 3D geometry. The interactive flavor of a *user-editor-viewer* liaison gives the human element a game-changing opportunity to manipulate geometry by leveraging *scripting* as a proxy to master its veiled morphogenetic processes. Parametric models sprout as a “living matter” reacting to modifications of input with a self-adaptation flow along the *associative* bonds of the algorithm, which make possible to unlock a *responsive* output. The geometric translation of a terminal point in a line segment can be an example of this responsive adaptation. If the coordinates of this point are changed from {*x*, *y*, *z*} to {x^1, y^1, z^1}, the algorithm maintains the established condition that the line is defined by two points, not by the location of each (Tedeschi, 2014; Woodbury, 2010). Algorithms establish *associative* relations between different entities such as numbers, geometric primitives and data[36]. For example, complex geometries can be defined by an unambiguous series of instructions that drive interrelations from a computational operator to the other. As an operational device for parametric design’s paradigmatic change in form generation, algorithmic modeling enables users to design a *process* rather than just a single object. The parametric object is never a single entity: it is, rather, the snapshot of an intricate, magmatic combination course.

However, we can appreciate the gradual affirmation of *visual programming languages* and *visual algorithms* as the most authentic and accurate operationalizations of a parametric diagram. This latter typology describes the grammar we will be focused on, since it represents the furthest evolutionary stage of parametric practice[37]. Similar to *scripting*, *visual scripting* is based on two main working environments: **A**) the *visual editor*, and **B**) the 2D or 3D modeling *viewer*. The concept of parametric diagram we have anticipated in the first chapter can be now reformulated as a *node-diagram*, a visual form of algorithm that inherits the articulation of graph nodes and links to set up composite constraint expressions, yielding a matrix of outputs constituted by *associative* 2D or 3D geometry as well (*fig.* X).

[36] Relations that, in a *parametric thinking* perspective, are based on a *performance* objective, as we already pointed out in section 0.1.4.

[37] As we will point out in sections 2.2.5 and 2.2.6.

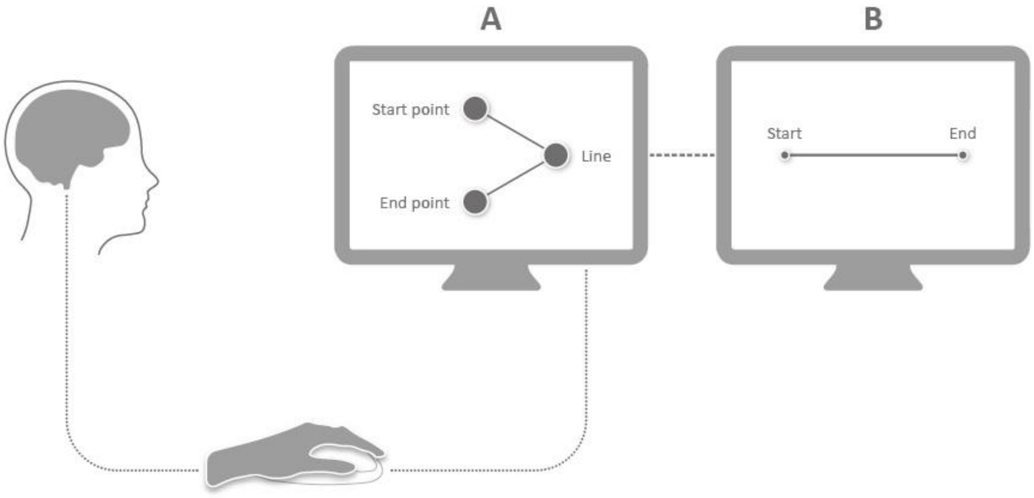

Fig. 21. In parallel with text-based *scripting*, algorithmic modeling based on *visual scripting* consists of two "windows": the *visual editor* and the 2D or 3D modeling *viewer* (elaboration from Tedeschi, 2014).

1.2.3. Specifying the *components* of algorithmic *scripting* in a performance-oriented parametric diagram: *input* components, *container* components and *standard* components

The aim of this section does not correspond to the recreation of a *scripting* manual, nor to a minute vocabulary of one specific programming language. However, some hints about the basic "anchor points" that can be edited while composing functions of performance through *node diagrams* still need to be unveiled, so that it would be possible to master navigation throughout the parametric canvas for our concrete application.

The following concepts of *visual* algorithmic modeling can be considered essential for both advanced *form-making* and vanguard *form-finding*. As we said in the previous section with reference to *scripting*, the modeling environment we are talking about consists of a *visual editor* that always works in parallel with the 2D or 3D *viewer* for a double-sided navigation (Tedeschi, 2014). Geometries undergo changes that simultaneously reflect the variable structure of their corresponding *node diagram*, which represents an array of elements forming a composite *constraint expression*. Interacting with the *editor*, users can build *visual* algorithms by properly connecting graphical objects in a *node diagram*. These objects can be either *links*, which represent the infrastructure of *data flows*, or *nodes*, which represent punctual plugs for *data management*, including manipulation, storage and processing.

The *nodes* of a visual *parametric diagram* that defines and controls a 3D geometry are called *components*. *Components* may represent *primitives*, *geometric operators* or *logical operators* at different rates of complexity. The overall coherence of relational ties through the set of intermediate input/output slots of these *components* is of primary importance, since proper syntax is a fundamental requisite for algorithms to generate results.

As we said before, *components* may perform as *primitives*, *geometric operators* or *logical operators*[38]. Typically, software toolbars group them in tabs, each organized in a number of panels. In turn, panels can also be expanded to enlarge the array of tools with dropdown menus, either to show web-imported or in-built supplements[39].

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[38] Examples of *primitives* can be points, curves and surfaces. *Geometric operators* include vector-driven transformations, such as extrusion, rotation, revolution and translation along a specific axis. *Logical operators* may involve "*true or false*" crossroads, with the purpose of forking data flows, or even "*if*" clauses, with a role of conditional statements.

[39] Of course, software platforms boasting watchful development teams, such as Rhinoceros with *Grasshopper*, point to diversify these panels according to criteria of rational combination, in order to furtherly enhance the understanding of associative bonds in the canvas.

As discussed in the introductive section of this chapter, an algorithm is a procedure that splits a complex task into a basic *corpus* of well-defined instructions. Analysts and designers can develop such algorithmic structure through either a *textual* or a *visual* sequence of (logical, mathematical, geometric) operations. *Visual algorithms* distinguish themselves for a friendlier interface, where the single *components* of the procedure can be quickly recognized, dragged and plotted down in the data flow along the incremental growth of the diagram.
In order to produce working algorithms with no risk of "jamming" their genetic channels, it is now crucial to understand how *components* operate. We can define three types of *components*:

1. *Input components – Input components* provide data, such as numbers and colors, which can be directly manipulated by scrolling the values after editing domain, format and connections with the overall diagram. An important property is that *input components* do not expect input data: as such, they can be interpreted as the variable "winglets" at the root of each branch of a parametric dendrogram. The so-called "*sliders*" represent a usual option for controlling the "flow rate" of numeric quantities.

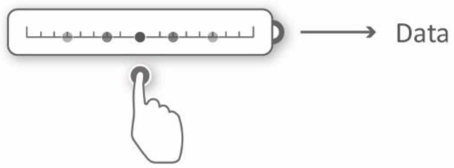

Fig. 22. Schematic representation of an *input component* (elaboration from Tedeschi, 2014).

2. *Container components* – These components can be imagined as receptacles for data. Their role consists in collecting, storing and illustrating data that may need to be monitored at some point of the diagram. *Container components* can also guard data imported from outer sources, such as *Geographical Information Systems* or cell-based spreadsheet datasets like *Excel* tables, and employ them as input for other components. In this latter case, *container components* rather assume the connotation of an "enlarged" or "manifold" species of *input components*. Container components may disclose a distinct versatility, but each of them expects a uniform data format, such as the type of geometry they are pledged to store: for instance, point-oriented *containers* can collect a quantity of points, but not curves nor planes.

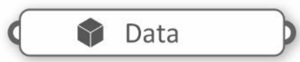

Fig. 23. Schematic representation of a *container component* (elaboration from Tedeschi, 2014).

3. *Standard components* – This last, but not least category represents the *components* that perform processing operations on data. As a necessary requirement, these components expect a defined set of input data, which is processed to generate an output according to their geometric complexification patterns. For example, the point-component requires a set of numeric {*x*, *y*, *z*} coordinates as input data in order to generate a point as an output. Similarly, a loft-component requires a defined set of curves as input to generate a surface as an output. Following such incremental assembly of *primitives* through *geometric* or *logical operators* toward more and more sophisticated shapes, *standard components* allow to re-use their own output as an input for another *component*.

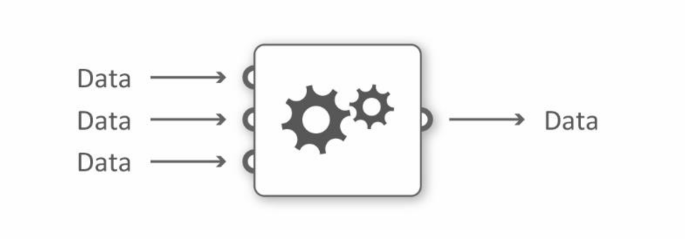

Fig. 24. Schematic representation of a *standard component* (elaboration from Tedeschi, 2014).

Standard components can be considered as central to the discipline of a morphological performance, for they regulate the substantive content of algorithmic instructions. The different levels of concatenation achieved by this latter category mirrors the different ranks of complexity of the *node diagram* together with the increase of parametric inputs, which innervate the data tree through an incremental process.

As a *standard component* is placed on the *associative* canvas, it requires a defined set of data in order to perform a task and generate an output. This type of *components* usually consists of three slices: *input slots*, *name* and *output slots*. The two lateral slots may vary from one to a definite plural number in asymmetrical ways. Generally, *input slots* tend to be higher in number, due to the fact that *operators* describe the synthetic convergence of several raw data toward distilled forms. The following figure shows the three slices with reference to a generic *standard component k*.

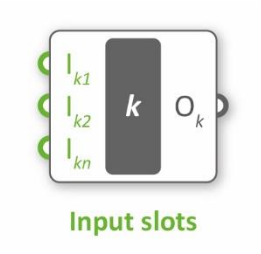

Fig. 25. Selection of *input slots* in a *standard component k*. They can be of variable, but always finite number, which is specific to each *standard component*. Although this is a general scheme, we can relate it to the example of points. In a 3D reference system, a "construct point" component requires three *input components*, i.e. the {*x*, *y*, *z*} coordinates. Each *input slot* needs properly formatted data.

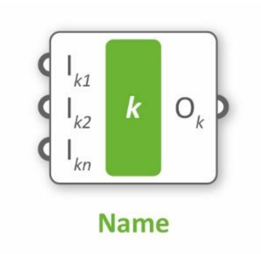

Fig. 26. Selection of the *name* in a *standard component k*. In software platforms based on *visual programming*, such as *Grasshopper* for Rhinoceros, this slice simply shows an understandable abbreviation. However, each *component* can be manually renamed by act of clicking. Alternatively, some software menus allow displaying an icon instead of a textual name, for purposes of sharper intuitiveness.

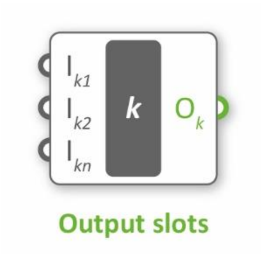

Fig. 27. Selection of *output slots* in a *standard component k*, in this case one. This slice shows a variable number of outputs that are specific to each *component*. Complex *components* may yield higher numbers of *output slots* according to the specific nature of their task and role in the system. In case of a point, the *output slot* generates data in the form of (one) correctly formatted point.

Standard components are the key elements of algorithmic instructions between input data and output model. This being the case, ensuring a meaningful graft of each of these components within the diagram becomes an essential requisite for working algorithms. This objective can only be achieved at the condition that each component exchanges data by properly matching its own slots with compatible outer slots. Patterns of compatibility among different slots arise according to the distinctive task of each parametric node of the tree.

Thus, a working algorithm needs data to be set inside the complete set of components in strict conformity with the format supported by each of their input and output slots. Users can anchor data to components in diverse ways. We can distinguish three non-exclusive modalities: *local setting*, *setting from the viewer* and *wired connection*. In the first case, data can be set directly from standard components, editing the content of input slots through context pop-up menus[40]. In the second case, some software tools let the user to set data from geometry that has already been traced in the *viewer* through click-based selections, with no reductions whatsoever in associative strength[41]. However, *wired connections* tend to prevail with the increase of algorithmic complexity. *Wires* conduct data from the output of a component to the input of another by pairing their respective slots.

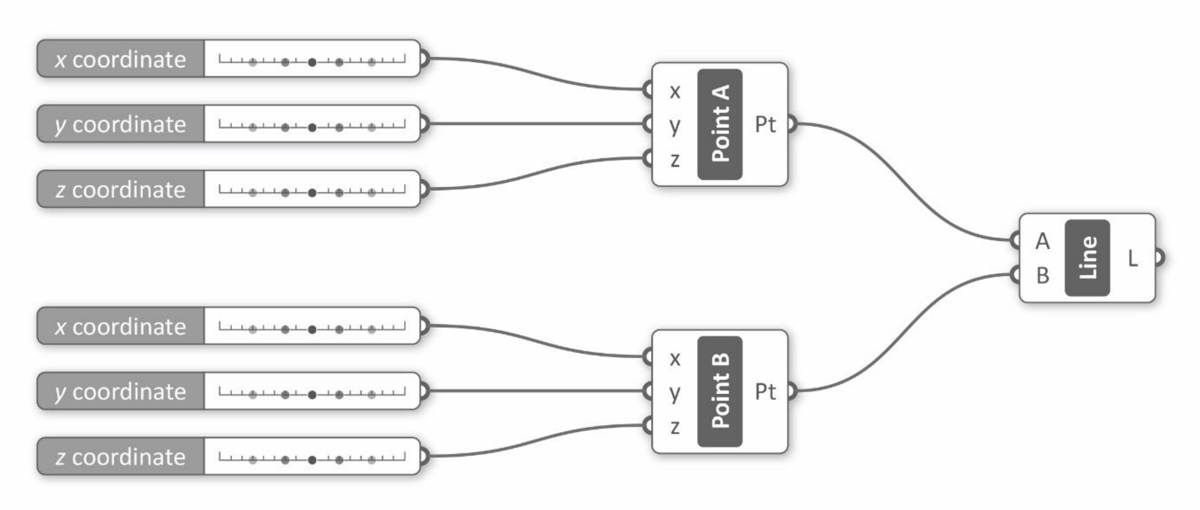

Fig. 28. Keeping the example of a line as the *associative* bond between two point features, we can reproduce its corresponding algorithmic diagram, as it would look like in a *visual scripting* canvas (elaboration from Tedeschi, 2014).

In the example, we can distinguish input components on the left, acting as roots of the "*data tree*", while standard components take place from the center to the right of the scheme. Point components can be considered as *primitives* of this parametric algorithm, whereas the line is the output expression of a *geometric operator* mating points *A* and *B*. *Wired connections* are privileged channels of data that give shape and direction to the diagram from inputs to outputs, at both intermediate and terminal locations. If we manipulate the values along the *sliders* on the left, we can expect the position of the two points {*x*, *y*, *z*} to be recalculated, leading to the *associative* update of the line in both magnitude and slope within a three-dimensional coordinate system[42]. Users can also disconnect and reconnect wires in different configurations, in order to reformulate data flows[43], but always keeping into account the compatibility of formats throughout the nodal components of the tree.
In fact, incorrect connections give rise to warning and error messages, which invalidate the production of tangible outcomes by blocking data flows. A *visual scripting* software can use background colors or "balloons" to

[40] Obviously, this aspect of manual "dexterity" calls for minding the formats supported by both types of slots little by little, since failing a fluid compatibility of data among components would basically mean compromising the actual reproduction of emergent geometries within the modeling environment.
[41] For instance, *Grasshopper* can incorporate existing Rhino geometry as an input datum through dedicate *container components*, even though with no chance to stretch back to the algorithmic construction that would have defined such geometry as an original *Grasshopper* object.
[42] In other words, the algorithm confers the status of parametric line to what would have been a simple trace in an *additive* perspective. The line is now tied *associatively* to our *slider* parameters, allowing for a dynamic generation of a set of lines defined by all the possible combinations of coordinate values within user-defined mathematical domains.
[43] Even in this case, these options can be accessed by means of context menus at one specific *input* or *output slot* of interest.

distinguish three possible conditions of components: *correct*, *warning* and *error status* (Tedeschi, 2014). A *correct status* describes components that are properly connected. The corollary of this is that working algorithms are composed of components displaying correct status only. Instead, a *warning status* is typically related to the lack of data. This may come about when complex operators are dragged on the canvas, since their rank requires data that cannot be established by default[44]. An algorithm displaying warning status somewhere may still work, but in general, a lack of data leads to unexpected or even null results. Finally, an *error status* occurs if users do not fulfill (some of) the input requirements.

Visual programming permits to differentiate *wired connections* as well. According to the specificity of each tool in terms of graphic choices, wires can assume a codified guise to inform users about their "cargo" grade in real time, where loads stand for the number of items involved, from time to time, in data transfers between couples of components. For example, in Tedeschi (2014, p. 57) we find that *Grasshopper* discriminates loads into three main types of data structure: 1) *no data*, with an orange connector; 2) *one datum* (one item, such as one number, one geometry, one text, etc.), with a thin black connector; 3) *two or more data*, with a wide black connector. The three "flow-rate" categories belong, in turn, to a basic rank of data structures, where connections share the aspect of *continuous wires*. In this sense, *Grasshopper* includes an upper level of data structures, described by *dashed wires*, which consists in networks of associative "heredity". These wires "telescope" and transmit data as grouped in "branches", where branches of later operations relate to items originating from the previous levels of geometric assembly. This transmission can be recursive too, meaning that the latest operation (i) spawns data structured in such a way that single items (numbers, strings, geometries) are grouped into branches referred to data spawned by ($i - 1$). In turn, these may be grouped into overarching branches referred to data outgoing from ($i - 2$), and so on, until we reach the first operator of such flow ($i - n$). Typically, dashed wires connote flows that come from operators whose role is deconstructing more or less complex geometries into their constituent primitives. The number n of hierarchical levels is proportional to the complexity of these geometries (Tedeschi, 2014).

We come upon such pattern of hierarchic aggregations even within the blunt assertion that Kevin Kelly (1952-), a renowned scholar in technology and complexity theory, made few years ago with reference to the increasing intricacy of mechanical systems toward ever more clever (and autonomous) forms of action and thought:

> *«Complexity that works is built up out of modules that work perfectly, layered one over the other»* (Kelly, 2009, p. 316).

Such treatment of complexity appears perfectly in line with using algorithms as solvers that decompose design problems into subsets of smaller problems, whose wires, when conveniently arranged, forge connections linking intermediate solutions toward the re-composition of a final one.

It is vital to understand that the allocative pattern of wires reflects the sense of parametric diagrams as *directed graphs*. In fact, wires can only connect the output of a component (A) to the input of a component (B) that does not precede (A) in the algorithmic sequence (Tedeschi, 2014). In other words, the data stream can be imagined as a "magmatic" fluid that flows through the series of components from left to right, channeling the solutions computed through intermediate constraints and converting them to new problems that would be finally solved through end operators. According to such logic, it is not possible to create a loop in a parametric matrix, except using specific components[45].

[44] For instance, a line can only be defined by precise locations of terminal points; otherwise, it would not be generated at all. The component automatically turns into correct status only if the user establishes proper connections with the needed operators and parametric inputs.

[45] This aspect will be discussed in the next chapter with reference to *generative* re-computation cycles as sources of forms that approach optimal performance. The solver *Galapagos*, aside from its specific role, is one of these special components and runs in *Grasshopper*'s environment (Tedeschi, 2014).

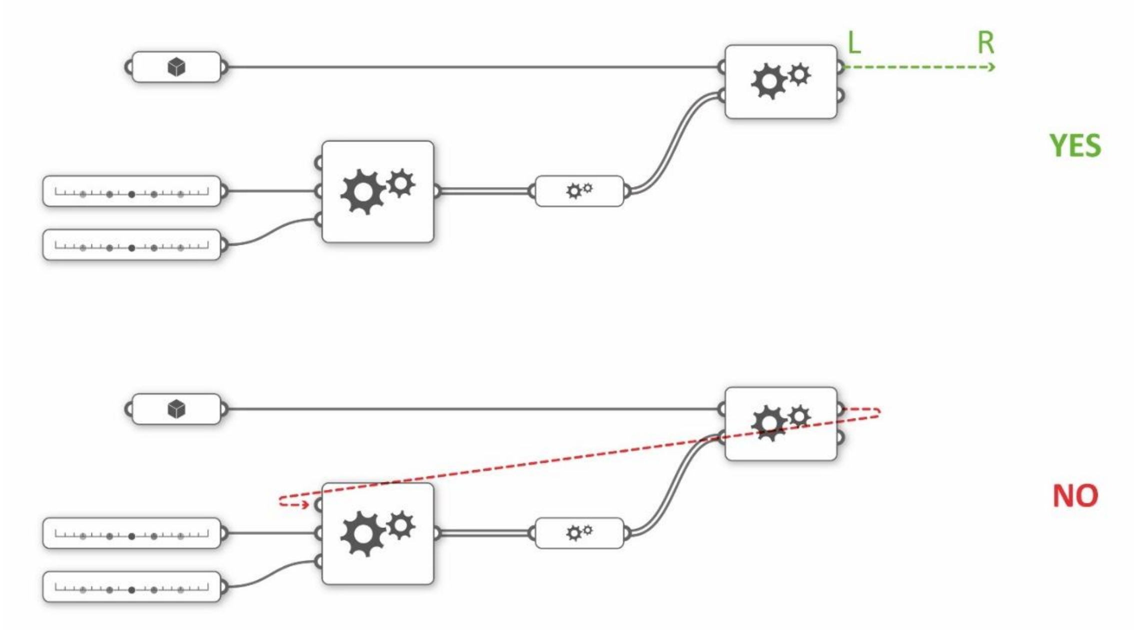

Fig. 29. The "construction history" of forms assumes strict directivity from root parameters and input storage, to ever more advanced associations of geometry, depicting a flow that intercepts and connects components from left to right (at the top). Such directivity cannot leave room to the reproduction of loops, due to a deterministic "heredity" of new inputs as outputs of previous components (at the bottom) (elaboration from Tedeschi, 2014).

The essence of node diagrams as "constructive" sequences, which, we remember, are laden with unambiguous directionality, is closely related to the impacts of enabling and disabling components across the morphogenetic process. Wired connections represent what structures and sustains the pattern of these flowing impacts throughout the system. With no wires, enabling and disabling components would both be uninfluential options, unless we set input values directly through context menus[46].

Once a component is disabled, it will no longer operate; but of course, the process is reversible. In *Grasshopper*'s lexicon, a disabled component can be distinguished by a faded gray color "switching off" the three slices (input slots, name and output slots). It is highly important to recall the underlying *associative* logics of a matrix: disabling a component means disabling all parts of the algorithm that rely on that node for their input resources (Tedeschi, 2014).

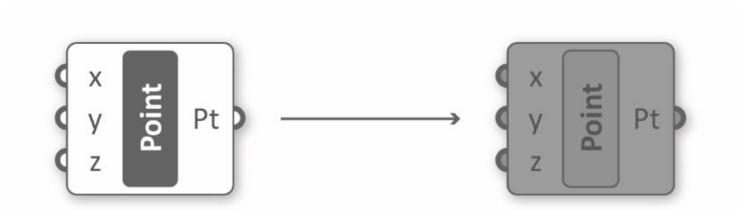

Fig. 30. Schematic representation of a component for point construction (on the left); the same component as switched off and consequently unable to store and transmit any datum (on the right) (elaboration from Tedeschi, 2014).

[46] In this case, the algorithm shall work, but would not support neither dynamic variation of inputs nor automatic updates of the final outcome, freezing the system and leading to prohibitive management costs for human elements. This would invalidate, clearly, the very idea of a gradient to be explored, simply turning to static one-off instances.

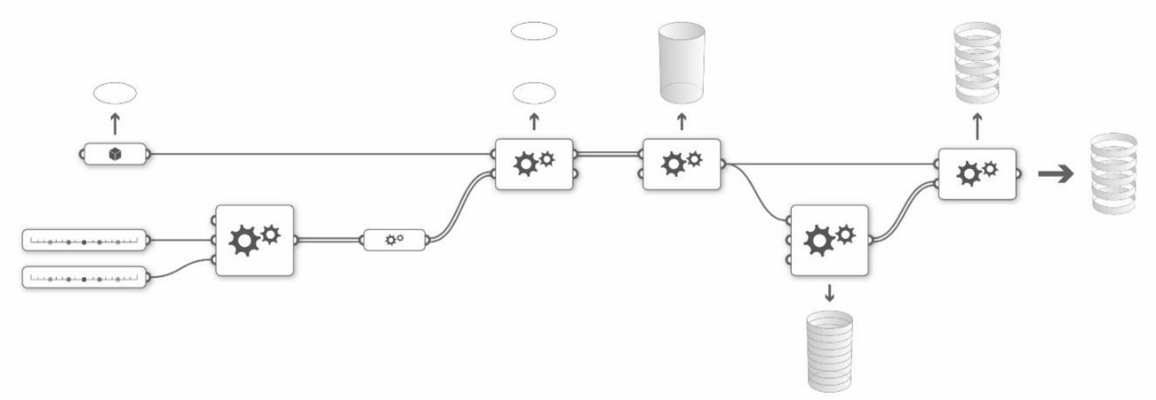

Fig. 31. Schematic representation of a node diagram "channeling" intermediate outputs (at the top/bottom of relative components) toward the final (on the right). All components are switched on (elaboration from Tedeschi, 2014).

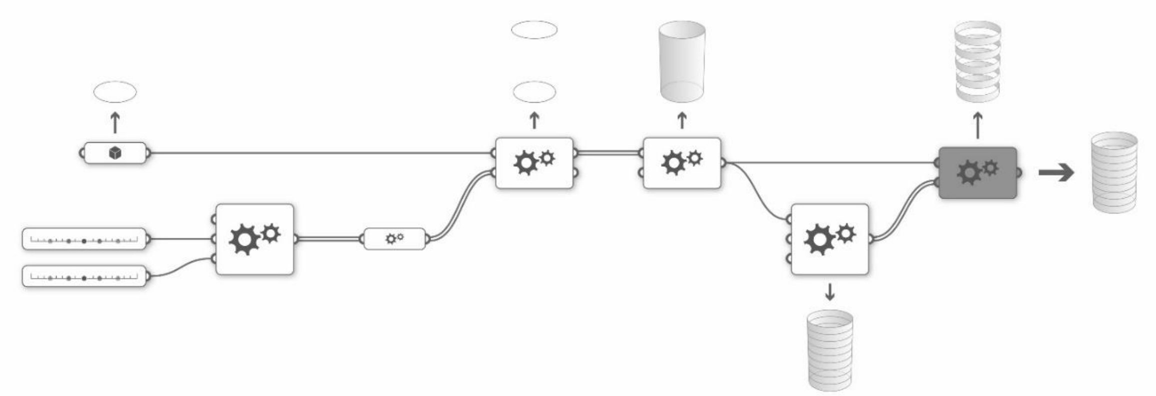

Fig. 32. The manifestation of graph directivity comes about as we switch off components along the process. In this case, the final output outgoes from the step that immediately precedes the last component (elaboration from Tedeschi, 2014).

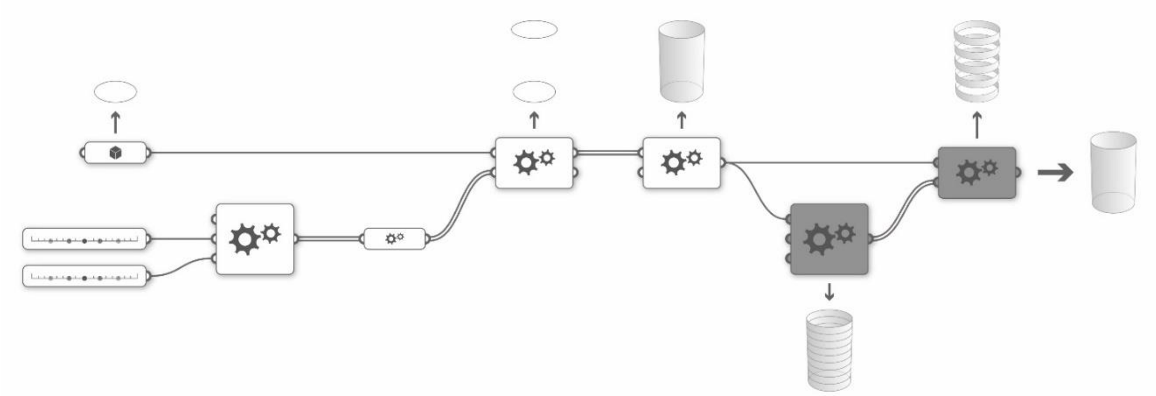

Fig. 33. Disabling components along a backward sequence confirms the correspondence between final output and the last intermediate output that is left operative, with a role in ending the process (elaboration from Tedeschi, 2014).

Such connections are not only accountable for a real-time modification of the model, but they constitute the essence of *associative dynamics* in a parametric morphology. Besides, *wires* define the *directed* nature of data flows from inputs to outputs, which leads us to consider the surge of dependency regimes across the sequence of *components* that give substance to a parametric diagram. In other words, we can recognize that the configuration of *wires* within the system is of primary importance if we need to understand the logics of *propagation effects* and the "self-adjustment" of formal outcomes at every parametric move. This is due to the close relationship that both the series of processing *components* and their cabling system of *wires* have in common with the definition of an explicit *function* of performance for design synthesis (Davis, 2013).

1.2.5. The *autopoiesis* of associative systems across the algorithm: hierarchical dependencies and propagation-based responsiveness between parameters and outcomes

Algorithms can define virtually every type of geometry thanks to how well they reproduce the sound combinatorial nature of a parametric tree. The procedural method to construct geometries, which tracks the explorative incrementalism towards an increasing morphological complexity, is based on translating modeling practice into the lexicon terms of a *programming language*. Such terms are typically *visual* in parametric modeling practice. The image below (*fig.* X) will serve as an example to explain the close nexus between visual programming syntax and responsive outcomes. It can be sketched by writing the following list of instructions: *1*) draw four circles; *2*) subdivide the four circles into *N* parts to get *N* points for each circle; *3*) finally, connect the corresponding points to get just as many lines.

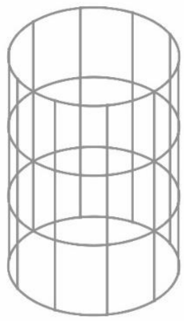

Fig. 34. An example model generated starting from four circles, with subdivision points connected to enforce structural stability (elaboration from Tedeschi, 2014).

The same model could be defined by different parameters, but it seems natural to write an algorithm in a way that establishes relations among the variable parts of an object (Tedeschi, 2014). In this example, the number of lines is affected by the number of subdivisions *N*, which represents the root parameter of the "*data tree*". Nevertheless, the procedural "recipe" is still ambiguous. In fact, it fails in specifying the complete set of required information for reproducing the same model, whatever the number of iteration cycles. In particular, we ignore: the definition of unique origins with respect to the *z* coordinate, $\{x, y, z^1\}$, $\{x, y, z^2\}$ and $\{x, y, z^3\}$; a radius for each circle (R^1), (R^2) and (R^3); the alignment of corresponding points through the series of circles, and even the method of connecting such points. For instance, points may support either longitudinal or staggered connections, leading to either a stereometric or triangular lattice.

The final algorithm cannot miss these refinements in the precision of inputs. Thus, the transition from rough drafting to algorithmic programming is a decisive moment for a working parametric model, in which the whole is responsive to changes in every part of the design (Tedeschi, 2014). The final algorithm expresses, in a *textual* or *visual* form, the relational structure of a *parametric diagram* in which *nodes* correspond to *input*, *container* and *standard components*, while *links* intertwine such nodes in a *binding function* representing a *directed* data flow towards the *output*.

In textual algorithms, *nodes* are steps of a written procedure, and *links* stand for both the overall sequence and the relational patterns described by each step. Instead, *visual* algorithms leverage the graphics of *node diagrams* to create *associative* geometries in an even more accessible workflow, not only as witnessed by the recent developments in software production[47], but also as anticipated by illustrious forerunning studies at the basis of

[47] Here we refer especially to packages like *Generative Components* and *Grasshopper*, whose *visual editor* windows allow for more intuitive *scripting* sessions even when designers have little to no programming skills.

computational design[48]. With the following figure, we get to the visual transposition of the procedure drafted in the previous page. The diagram's output is the exact geometry generated through the step-by-step chain of text-based tasks.

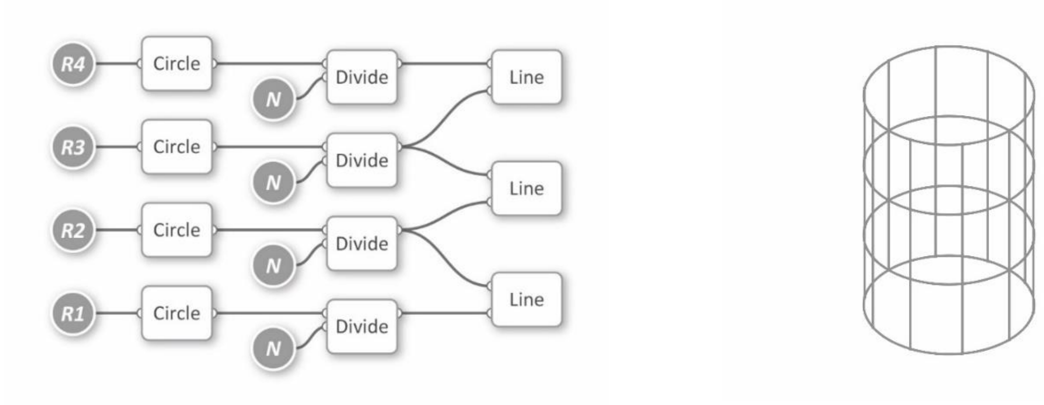

Fig. 35. An example model generated starting from four circles, with subdivision points connected to enforce structural stability (elaboration from Tedeschi, 2014). In this case, the model has been reproduced in *Grasshopper*'s environment.

Again, let us notice that the diagram consists of *nodes* and *links*. In this simplified representation, square nodes are the main *geometric operators*, which fall into the family of *standard components*: first, draw a circle, then divide a circle and, finally, create a line. Circular nodes are the independent parameters, i.e. the *input components*: the radius (*R*) of each circle and the number (*N*) of subdivisions.

The character of a *node diagram* resides in its interactive logic, which allows you to quickly notice structural changes in the model as the single values of parameters move along their domains. Keeping our example, if the *N* parameter is modified, more lines are generated. More precisely, even a slight change in the number of subdivisions implies that the number of lines behaves accordingly. This is because the operator "Line" is hierarchically subordinate to the "Divide" step, which, in turn, incorporates the number of subdivision points. This network of linear hierarchies from the left to the right gives the diagram a precise *directed* status.

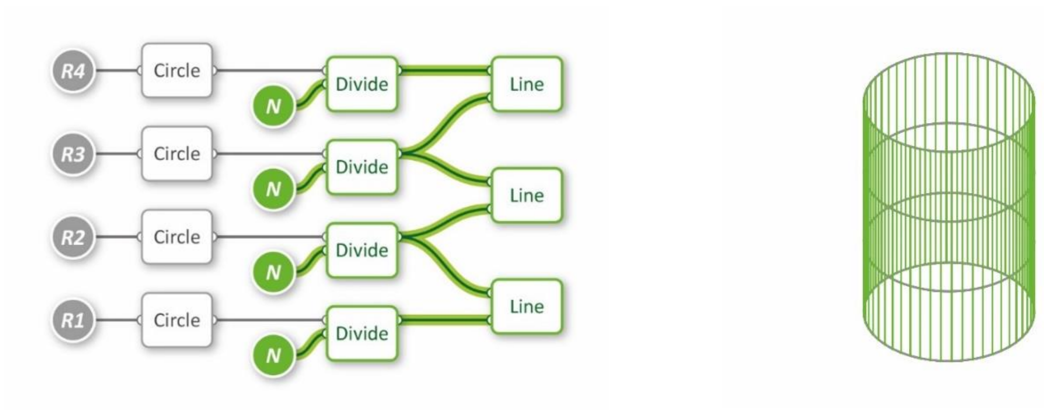

Fig. 36. An example model generated starting from four circles, with subdivision points connected to enforce structural stability (elaboration from Tedeschi, 2014).

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48 We refer, in this case, to Sutherland's pioneering experience with the software *Sketchpad*, in the 1960s. Despite visual definitions of algorithms came to light only recently, *Sketchpad*, as the first digital parametric tool, had already outlined a definition of basic rulesets through a combination of elementary instructions expressed in a graphic language (Sutherland, 2003). A dedicated narration of this reference will take place in section 2.2.2 so as to define the complexification patterns of digital parametric design.

The independence of parametric inputs and the capillary engulfment of in-between operators clearly emerges as we highlight the *propagation effect* of the diagram. We can see on both sides of the figure that radiuses (*R*) are not affected at all by the change in the number (*N*) of subdivision. Parameters are the starting roots of every data tree, which is due to the inherently terminal nature of *input components*. As such, they rather drive propagation flows through a web of dendritic dwindles, without being directly affected by propagation itself[49].
Our geometry can be furtherly modified by manipulating one of the (*R*) parameters. In the following figure, we can see the increase of the third radius from the bottom (R^3) with the corresponding *propagation effect* in both the visual algorithm and its real-time modeling response.

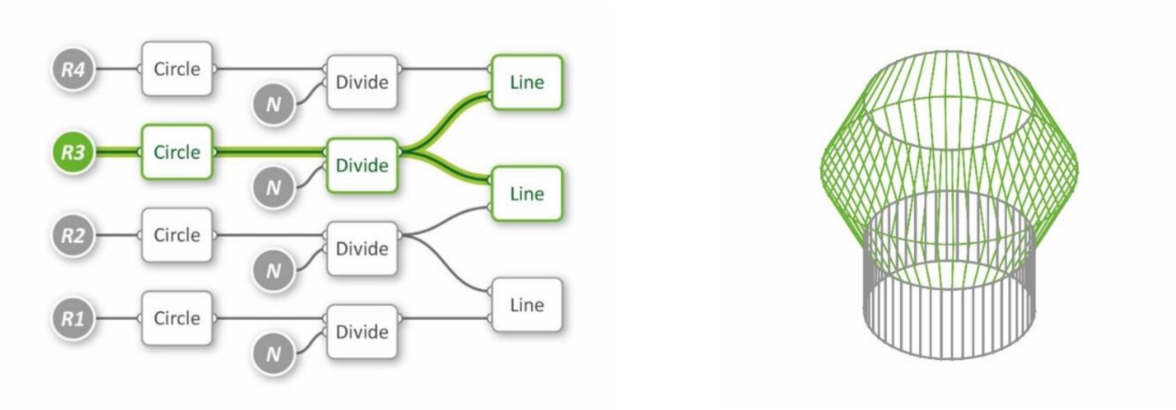

Fig. 37. An example model generated starting from four circles, with subdivision points connected to enforce structural stability (Elaboration from Tedeschi, 2014).

There are virtually no limits to the number of remodeling sessions, aside from the computational speed of the machine. Geometry can be once again modified, this time by manipulating the whole set of radiuses simultaneously (R^1, R^2, R^3 and *R4*), as shown in the next figure.

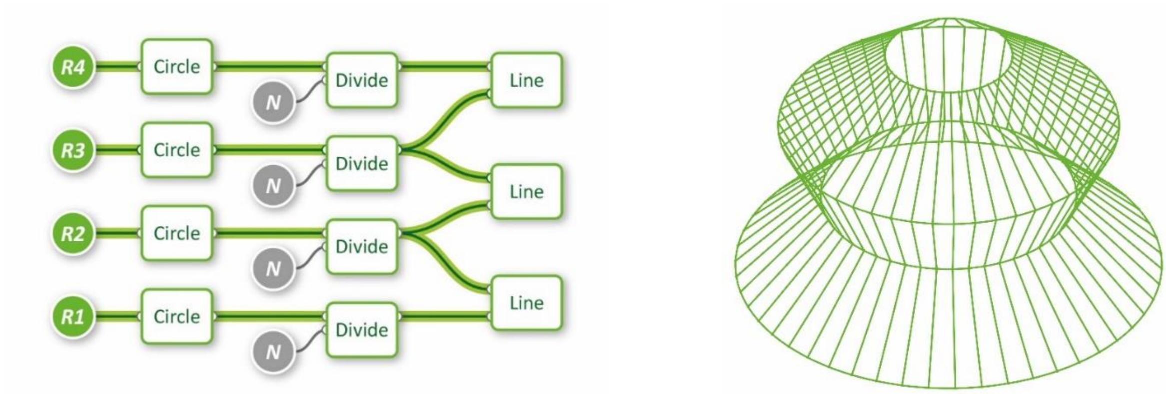

Fig. 38. An example model generated starting from four circles, with subdivision points connected to enforce structural stability (elaboration from Tedeschi, 2014).

As we can see in this last case, the *propagation effect* originates from the extreme left branch of the visual algorithm, leaving unchanged, on the one hand, the number of subdivision lines, and affecting, on the other hand, their slopes according to the radius of each circle. This is due to the very pattern of *wired connections*, which

[49] This holds for basic algorithmic matrixes, which compute data transfers from input to output slots *once* for each parametric alteration. In the next chapter, we will couple this *linear* form of arranging data flows with a recursive or *circular* expression, which is possible through components explicitly dedicated to automatic re-computation of outcomes over a number of iterations. See section 1.3.4.

gives shape to the telescoping regime of dependency that each point of the model entertains with the size of its corresponding circle.
Propagation can be considered as an inexorable consequence of *associative* models governed by a *directed* data flow. As we have seen through the example of the basket, the outcome model always shows a degree of *responsiveness* to every input variation, due to an informing system of correlation rules. This means that outputs are not anymore static images: instead, they bear a default ability of adapting to parametric changes automatically, always restoring their original conformity through spontaneous regenerations. This property of persistent self-adjustment is specific to diagramming through algorithms, can be defined as *autopoiesis* (Schumacher, 2010). In brief, autopoietic models owe their "self-adjustment" character to a specific emphasis on designing an open *process* rather than focusing on a "final" *outcome*[50] (Cecchini, 1999).
Through the control of input parameters, this effect assures to appreciate the ability to explore multiple configurations by starting from the gradual assembly of malleable *primitives*, in a vanguard quest for new forms. As recalled by Patrick Schumacher (2010), one of the major theorists, enthusiasts and advocates of parametric design:

> *«While the attributes of the graphic/digital primitives [...] are fully determined and fixed at any time, within the parametric diagram they remain variable. This variability might be constrained within a defined range on the basis of associative functions that imbue the diagrammatic process within an in-built intelligence»* (Schumacher, 2010, p. 352).

The parametric diagram can be considered as a "smart medium" (Tedeschi, 2014, p. 30) for architecture and design, since it provides an internal self-consistency transposed in a graphic language, which can be easily manipulated, enabling designers to explore not only new *form-making* strategies, but also *form-finding* opportunities. Jerry Laiserin (2008) can also be quoted with reference to *form-making* and *form-finding* practices that result "augmented" by algorithmic modeling:

> *«Form-making, loosely defined, is a process of inspiration and refinement (form precedes analysis of programmatic influences and design constraints) versus form-finding as (loosely) a process of discovery and editing (form emerges from analysis). Extreme form-making is not architecture but sculpture (perhaps, folly) – form without function. Extreme form-finding also is not architecture but applied engineering, where form is exclusively determined by function»* (Laiserin, 2008, p. 236).

[50] In other words, assembling an *abstract* matrix of possibilities instead of a fixed, *concrete* object. Through this dualism between abstraction and concretization, we make explicit reference to a basic principle of *parametric thinking*, which we described in the subsection 1.1.4.1.

1.3. The *generative* root of parametric modelling: space as an exploratory matrix of morphological opportunities addressing the complexity of urban evolution

1.2.1. The founding principle of *generativity* in urban massing and morphological modelling: conceptual definition, evolutionary settings and self-organizational logics

Since parametric design methods represent the algorithmic automation of a morphological profiling process, which is carried out by prefixing specific formal standards to reach the desired compositional results, the close relationship with generative models and, more generally, with the very concept of *generativity* becomes evident. Despite this principle is incorporated by the parametric method only partially[51], describing the meaning accrued in the literature, with particular regard to the impulses of some illustrious forerunners[52], will be needed to recognize its foundational importance for the process of elaboration through which input parameters go during electronic computing sessions.

The reference to the role of machine in the design of urban form may already present itself as a possible starting point for clarifying what we mean by *generativity*, in order to avoid terminological misunderstandings[53]. *Generativity* is in fact a property that we can already notice in the Darwinian behavior of living organisms, even before the most recent computational applications (Puusepp, 2011). Informatics played indeed as an instrument to transpose, within the linguistic limits of programming codes, such evolutionary dynamic to artificial intelligence (Cecchini, 1999). As well as organic species undergo continuous mutations by reacting to the alterations perceived from time to time in the surrounding environment through adequate behavioral patterns, similarly settlement fabrics are never a final product, but the intermediate picture of a cyclical feedback mechanism to contextual conditions subject to continuous change. *Generativity* can be read, therefore, as a property purely aimed not at securing a formal product, but to a never-ending evolutionary process toward forms that mirror the iterative adaptation to variable conditions, along the path to optimality (Puusepp, 2011). A process, we could say, which continuously adjusts the genetic code to guarantee success in the struggle for survival, where the code represents nothing but the informational heritage according to which a particular form propagates itself.

In line with this conceptualization, generative design fully embraces an interpretation of the urban project not as an imprinting arbitrarily preconceived by a "demiurgic" decision-maker, but as the emergence of transient configurations in response to contextual tensions of changing nature (Donato, 1996). The approach proposes, therefore, to favor a congenital dynamic of the city-organism, by tracing an evolutionary process in search for the most appropriate urban forms to solve a specific design problem. Exactly as living species adapt to the obstacles of their own environment, by gradually "perfecting" themselves in their relationship with the territory.

Evolutionism can be found in the dynamic iteration of tests applied to emerging forms, in view of a progressive adaptation to contextual conditions. More specifically, the evolutionary emergence of geometries in the model is due to a procedural cycle, which starts from the collection of analytic reports as input data and engages in a

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[51] The two adjectives *parametric* and *generative* refer to approaches that do not completely overlap, despite sharing the basic notion of *generativity*. We will see more in detail such distinction in the last section of this chapter, focusing on the evolutionary expansion of parametric algorithms.

[52] Among the several contributions within the literature, we have selected some relevant considerations exposed by Jane Jacobs, Bill Hillier and Christopher Alexander, together with a brief reference to Michael Batty's works: we have intended these figures as decisive "milestones" for a reliable interpretation of the urban armor in relation to its generative character. Section X will be dedicated to the appreciation of these studies.

[53] Misunderstandings that urban planning, as a perpetually developing discipline, needs to dismiss in order to stabilize its scientific core. This means not only calling for an act of "polishing" the academic lexicon. According to Puusepp (2011), the term *generative* tends to be abused in a brush attempt to obfuscate the traceability of design methodology, which could result in making outcomes sound "esoteric" and, thus, resistant to constructive critiques.

closed circuit the other two central moments of the design process to finalize the analysis: *synthesis* and *evaluation*[54]. As such, it does not go on linearly toward a static output (Puusepp, 2011). With the support of computational technology, the reproduction of a dynamic adaptation for compositional solutions occurs by structuring an algorithm that, by providing periodic *tests*, reflect such a circuit. In this way, the closure of the algorithmic path automatically reshapes a geometry according to *feedback* mechanisms in which the system, by comparing the performance of a morphological hypothesis with the satisfaction of contextual conditions, interprets the output of each evaluation as new input data in a continuous learning process, until compositional optimization (Puusepp, 2011). That being the case, closing the circuit is in fact a key condition for the dynamic *generativity* of this quest. Meanwhile, the use of refined algorithms, by means of ever more sophisticated computational automatisms, tends to simulate the natural process better than the human element could ever carry out, sometimes leading to inedited settlement patterns in a consistently narrower time span (Donato, 1996; Frazer, 1995).
The emergent tension of these patterns can manifest itself not only through temporal evolution, but also along a scalar dimension. In this respect, the pattern is identified as the global result of an algorithmic aggregation between its constitutive elements at the local level. In this case, the *genetic code* corresponds to the apparatus of rules that, by defining the behavioral regime for local elements at the micro-scale, determines a compositional solution as a result of propagation across the macro-scale. This scalar declination of the principle of *generativity* distinguishes the *evolutionary* models described earlier from *self-organization* models (Puusepp, 2011), whose *Cellular Automata* (CA) are perhaps the most common example (Batty, 2007; Cecchini, 1999). Applications of these models have been developed not only for purposes of geographical analysis, but also for assisting the design of the built environment, ushering the exploration of morphological solutions based on local interactions among cells in three-dimensional matrixes (Puusepp, 2011).
It seems needful to recognize that the concept of *generativity* in the design field has no headless origin, but it rather descends from the influence that evolutionary research, once rekindled by the discovery of genes in the 1950s, has exerted on other fields of human knowledge. These include precisely the architectural and planning ones, leaving themselves to be intercepted by subsequent advances in computer science. Scholars such as Christopher Alexander and Michael Batty were well aware of the fact that reserving a portion of their attention to the research that gave forth to *generative* approaches would have shed light more explicitly upon the rationale by which the evolutionary cycles of urban form come about over time (Mehaffy, 2008).
By recalling their interpretative vision of the city, the affinity between the morphogenetic conceptualization of settlement fabrics and the application of an algorithmic procedure would be clarified, since the latter stands as a mathematical simulation that reproduces the transcription of a *genetic code* expressed by means of a transformation rule.

[54] Together with the *analysis*, *synthesis* and *evaluation* are commonly shared concepts for describing the phasing stages of a design process (Puusepp, 2011). The origin of this repartition originates in Lawson (2006), who defines the three steps as areas of negotiation between problem and solution. Despite the three stages tend to blend into overlapping patterns in practice, we can still distinguish the role of each. Carried out as a point of departure, the analysis consists in the delicate task of formulating the design problem. Design solutions to the problem are generated at the core stage of *synthesis*, where designers are asked to display a creative effort in diverting the polarities of multiple local problems and making ideas converge into a proposal. The *evaluation* stage serves as a testing, appraising and monitoring device for synthetic solutions, sometimes helping in questioning the demands raised during the analytical stage. Tools are typically tailored for each stage, reflecting their different roles within the process.

1.2.3. Three visionary efforts concretizing the genetic similarity in urban planning by recognition of an *organized complexity* in city development over time

The transposition of the concept of *generativity* from the achievements in genetic fields to the analysis of the evolutionary mechanisms characterizing the built environment has been proposed over time as an effective expedient to concretize the idea of an *organized complexity* at the base of the phenomenon city. The interpretation of the city as a complex system, to be disentangled through the instruments of a *science of complexity* (Batty and Torrens, 2001), affirms the existence of a hidden order within the urban armor (Donato, 1996), which is the result of multidimensional dynamics, differentiated intensities and dendritic interactions. *Complexity* is the structural property that distinguishes a system forged by interconnections, causes and effects at different scales and voltage levels; in turn, these elements show multiple combinatorial and variable nature. As such, the concept relegates *chaos* to appearance, by casting glimmers of intelligibility toward settlement palimpsests through their gradual evolution[55].
These glimmers concern the ability to decompose the complex system in its different dimensions, in order to investigate their dynamics singularly. The use of urban models fits into this perspective: they represent, in effect, an attempt to reduce complexity along a specific directrix (Paolillo, 2010). This does not mean, however, that the city can be fully understood (or manipulated) by means of any instrument of simplification, especially if the tool purports to bring back, not without mathematical preciosities, the entire urban dynamic to a single elementary mechanism[56]. It rather means that it is essential to match the degree of sophistication of the model and the nature of the single aspect to be examined within the whole system. The reliability of the model can be read as a function of this correspondence[57].
The inevitable partiality of any attempt at modelling suggests to employ, at this point, a re-composition of the original complexity by means of a speculative integration among the single dimensions already analyzed. The epistemological turning point of the new investigative paradigm is evident in this latter procedural tipping. In fact, the intersection between different dimensions of complexity is structured around the awareness that the system is more than the mere sum of its components.

In doing so, it is suited for constructing a debate on possibility as it relies on a qualitative understanding of settlement phenomena rather than on predictions harnessed to an *a priori* and, for this reason, more incautious image of the city. As reported also by the renowned geographer and urban planner Michael Batty:

> *«The first 50 years of the last century, perhaps even the previous 200 years, was dominated by the notion that science would yield answers of the simplest kind to a wide range of applicable problems but this certainty has gradually dissolved. The reasons for this are diverse. At one level, this may be no more than one of those unfathomable psychological shifts in our awareness of the limits to our knowledge which occur periodically; at another level, it may be due to an increasing body of experiential knowledge of using science in the quest for exact answers to important problems and the growing realization that such certainty is illusory»* (Batty & Torrens, 2001, p. 3).

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[55] An example of this opportunity may consist in a verifiable principle of *self-similarity* that, according to Donato, Basili and Piroddi (1996), would describe, in its intimate rationale, the evolutionary organization of urban morphology with a good approximation degree, by applying the *fractal dimension* as an indicator of complexity.
[56] In this case, the failure of a model cannot be attributed to a supposedly scarce significance of mathematics in the explanation of territorial phenomena, but to the more profound "philosophy of intents" at the base of its application, as we will see few rows later.
[57] Of course, aside from the complying with complexity levels, a more general condition for a reliable model lies within a basic principle of independence (Puusepp, 2011), which is common to every hard-science domain. This principle states that a model should not depend on the set of data used for its calibration: it should rather accept different sets.

The shift pronounced by Michael Batty has not mortified the use of a technical-scientific instrumentation to describe or predict, within the approximation limits of the method, the trajectories of the city-system. It has rather chiseled its background rationale, by shaping the research around a new level of maturity. Until the first half of the 20th century, what distinguished theories and models was, in effect, the presumption of being able to expeditiously distill the essence of things, by capturing the reality of the territory on the basis of real reductionisms disguised as simplifications (Batty & Torrens, 2001). Despite the recognition of the complexity pertinent to settlement dynamics, the use of traditional theories and models, based on the reduction to a limited number of explanatory variables[58], was clinging to a large stretch to almost maneuver the observation of the territory so that reality concurred with its model (Puusepp, 2011). The contribution made by Batty, even though sitting on the shoulders of other big personas, as we will see, gathered the irreducible complexity of the urban system, opting for the adjustment of theories and models to unveil its principles of organization and, at the same time, abandoning any preordered hypothesis for the sake of a growing interpretative wealth.
Among the historical precursors of the concept of *organized complexity*, we have selected three authors that could be considered, together with their respective publications, as milestones of the paradigmatic change we have just described, in line with the contents of the *generative* thinking. Three volumes, three authors, but also three contributions different for the issues raised, the approaches proposed and sparks of debate: Jane Jacobs, Bill Hillier and Christopher Alexander.

Jane Jacobs, "The Death and Life of Great American Cities" (1961): questioning the failure of top-down master-planning in managing the complexity of urban development

The last chapter of the famous essay written by Jane Jacobs, "*The kind of problem is a city*", matches the city with the understanding of a complex system in which large amounts of factors tend to intersect in an organic product. By recognizing the scientific advances in the statistical, biological and computational branches in place, the author has questioned the implications that these could have exerted on the study of urban complexity, hoping that designers would seize the opportunity to equip themselves with up-to-date tools able to adequately define the multidimensional nature of a problem to be solved (Mehaffy, 2008).
However, Architecture and Planning, as she observed, had bogged down in methods tracing "Newtonian" style mechanics, believing that we could treat the problems of the city sometimes as simple two-variable questions, sometimes as cases to handle according to what suggested by summary statistics. Influential schools, such as the Garden City movement or Corbusian Modernism, were not immune to an historical misunderstanding between simplification and rationalization, not at all: they have been incorporated as a comprehensive approach to planning, with devastating results (Mehaffy, 2008).
Both movements were lying, in fact, on reductionist conceptions of urban-anthropic interaction: the first assumed, through diagrammatic inspirations (*fig*. X), the isolation of urban variables such as residences and workplaces; the second drew massive reconfiguration schemes (*fig*. X) from brief statistics on population, such as the number of household members and income classes:

> *«With these techniques, it was possible not only to conceive of people, their incomes, their spending money and their housing as fundamentally problems in disorganized complexity, susceptible to conversion into problems of simplicity once ranges and averages were worked out, but also to conceive of dry traffic, industry, parks, and even cultural facilities as components of disorganized complexity, convertible into problems of simplicity»* (Jacobs, 1961, p. 439).

[58] Also due to the binding limits of computing power during times that preceded information technology revolutions.

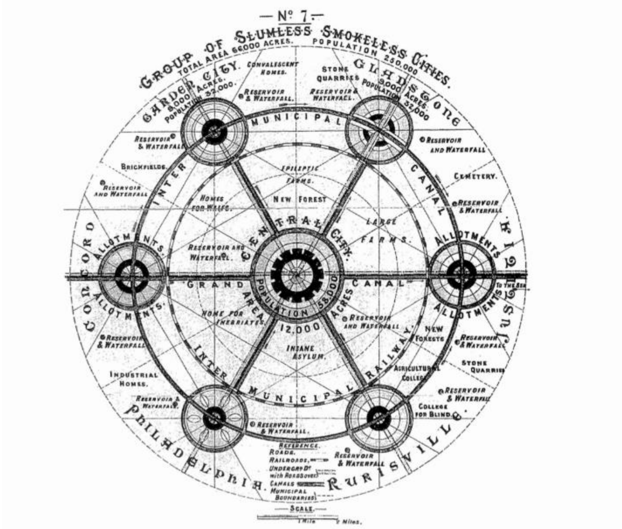


Fig. 39. Howard's *Garden Cities* diagram (retrieved from: https://scodpub.wordpress.com/).

Fig. 40. Le Corbusier's unbuilt *Voisin Plan* for Paris (retrieved from: https://it.pinterest.com/).

Combined with the positive stiffness of the planning form, the presumption of being able to overpass the depth of the problems with superficial solutionism proved to be a disastrous strategy for it had been unsuitable to grasp important organic relationships of the urban *process* and, on the contrary, it became fossilized in the *product* of an illusory anthropometry. The anticipation of the *generative* matrix began taking shape here, waiting for a growing sensitivity in the following years. According to Jane Jacobs's farsighted vision, Planning could no longer dare to subjugate the organic dynamism of the territories with an already packaged "end-state" because, by ignoring the developmental organization at the root of urban complexity, it would have continued to seal human interaction spaces within sterile, oppressive and dysfunctional environments (Mehaffy, 2008).

Bill Hillier, "Space is the Machine" (1984): an attempt to investigate complexity through a model for urban morphology centered on the patterns of network connectivity

The purpose of this paragraph does not contemplate a summary of *Space Syntax*, the theory formulated by Professor Bill Hillier and his colleagues at the University College of London in the early 1980s (Hillier & Hanson, 1984). Nevertheless, it is possible to re-read *Space Syntax* as an interesting attempt to treat the *organized complexity* at the base of settlement morphogenesis.
The reduction of urban space to a specific level of modelling abstraction[59] allowed, in this case, to reveal the intimate relational regime unleashed by the articulation of its components. Doing so, the approach has given shape and form to the hypothesis that the experience of the city lets itself to be driven by a primordial attraction, the *natural movement* (Cutini, 2010), which is directly dependent on the morphological quality of the urban itineraries instead of the single activities located along them[60]. In this case, the articulation can be explored, through dedicated *software*[61], under either topological or metric profiles, according to the kind of spatial impedance meets the interests of the analyst. In this perspective, the overall configurational state of a settlement,

[59] Within the configurational approach endorsed by Bill Hillier, this reduction is carried out by tracing out the diaphragms trimming the network of all the public spaces that can be freely traversed by the inhabitants of a settlement, typically street branches and squares. The pertinence area of such network, once traced from real-world spaces, assumes the denomination of *urban grid* (Cutini, 2010; Hillier, 2001).
[60] The distribution of urban activities is, indeed, nothing more than the consequence of the morphological quality performed by their localizations, which, in turn, depends on how these relate with all the others (Cutini, 2010).
[61] We refer here to *Depthmap*, a tool that analysts can freely download at the website http://www.spacesyntax.net/.

which represents the backbone of its centralities by means of *network analysis* indicators, rises as a consequence of the patterns of dependence, connectivity and interaction that each single minimum element of the urban web maintains with all the others due to syntactic propagation.

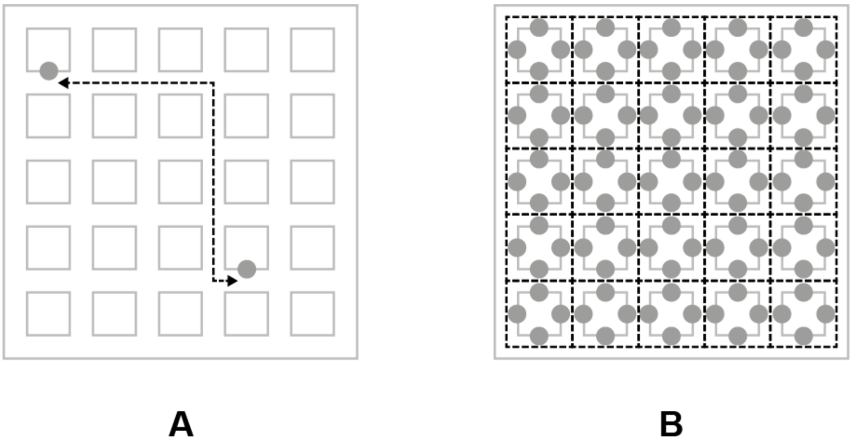


Fig. 41. The image shows the relationship between a stereometric *urban grid,* which results from an elementary pattern of visual obstacles, and the distribution of economic activities, according to different interpretative shades. *A* represents a consolidate view of movement arrays as the outcome of gravitational *attraction* among two or more activities, based on their presence, consistency and relative influence, independently from network layout. Conversely, *B* stands for a *Space Syntax* perspective, in which movement arrays respond primarily to the *configuration* of grid patterns, determining, in turn, a *generative* distribution of activities. In this case, the distribution reflects the evident morphological uniformity of the context (elaboration from Cutini, 2010).

The model boasts a well-established battery of applied researches, from which two key aspects emerge: on the one hand, the organic tendency of "central" activities to be located in correspondence to formal centralities; on the other hand, the failure of some decentralization plans, due, at least in part, to the connective weaknesses of the network (Cutini, 2010; Hillier, 2001).
The gravitation of central appeal levels, according to which it is possible to discriminate the urban armor by degrees of attractiveness with good approximation, manifests itself as the phenotype of a more hidden genetic principle of organization of local elements that propagates, through the network, the apparatus of its connectivity rules. Under this interpretative lens, we can deduce with further clarity the eminently *generative* make of the model, by glancing the evolutionary interactions between the configuration of the infrastructural layout and the distribution of functions.

Christopher Alexander, "A New Theory of Urban Design" (1987): a sound reasoning upon the synthesis of urban form toward combinatory patterns of evolution

We can recognize a *generative* interpretation of urban processes even in Alexander's milepost volume "*A New Theory of Urban Design*", by crediting its significant operationalization of *generativity* within the urban design field of practice. In particular, the author incorporates the challenge to the very notion of design as a technical exercise that simply follows a series of pre-packaged masterplanning products. The attention gravitates around the shaping process, with the recognition of an evolutionary synthesis of form over time. In Alexander's view, urban morphology needs to be seen as the emergent outcome of a mereological relation of parts and wholes (Mehaffy, 2008), which makes us notice at least a conceptual affinity with the *associative* rationale of parametric diagrams.

The production of *complexity* through evolutionary dynamics of aggregation has been an active conceptualization in biological fields of research; Alexander, as a scientist, was well aware of the potentials of this newborn cross-disciplinary trend. Besides, the development of cybernetics and computer *software* had been fueling the simulation of such processes since the post-war period. However, the organic permutation of forms was not to be intended as a biological analogy, but rather as a structural quality, which describes the city as the momentary image of a continuous interactive process among a plurality of participant actors. As such, the city could not be forced to a predefined concept of standard, conventional and frozen typologies. Thus, the author wanted to propose a methodology by which such a collaborative process could produce geometries that had the connotation of *organized complexity*, quality that he identified as "*wholeness*" (Mehaffy, 2008, p. 62).

As the city results from a series of incremental steps under transformation, the analyst and the urban design have to make an assessment about whether and how the proposed construction adds to, or takes away from, the *wholeness* of the city at each step of its evolutionary cycle (*fig.* X). The rule formalized by Alexander imposes one basic obligation for every act of construction: it should create a continuous structure of wholes around itself. In order to assure an effective appraisal for *wholeness*, the author introduces a geometric entity that he calls a "*center*" by honoring his mathematical background. In essence, *centers* are simply localities, or "spots" embedded within a web of other *centers*. *Centers* are not properly points, but rather fields inlaid in a puzzling combinatory gear. As Alexander puts it, a *center* is "*a whole, made of subsidiary wholes*" (Mehaffy, 2008, p. 63). This sorting matrix can be considered as an approximation of the *genetic code* of the urban system, whose structure represents a nested series of localities that frame one another in a pattern of mutual relationships. In turn, this pattern gives forth to an up-scaled field, which comprises its own up-scaled center. Conversely, every such *center* is embedded in a field of other *centers* that affect both its structure and the structure of the wholes that result from their combinations. On the other way round, it follows that every *center* incorporates other centers at smaller and smaller scales.

The image of urban design practice conveyed by the *New Theory* strictly denies the imposition of forms based upon a seemingly "rational" program, especially if this program pops up from a comfortable (but unrealistic) *tabula rasa* environment. Urban design should rather incorporate the decisions and needs of local stakeholders, as a matter not only of fairness, but also of the intrinsic quality of the result. Alexander reframes the act of designing as a result based on conditions for spatial development under an evolutionary light, rather than a series of predefined layouts across space. In this sense, design is a process-led approach, and a *generative* one of that, in which the synthesis of form cannot produce a stock of standardized objects, but local, adaptive and unique solutions (Mehaffy, 2008).

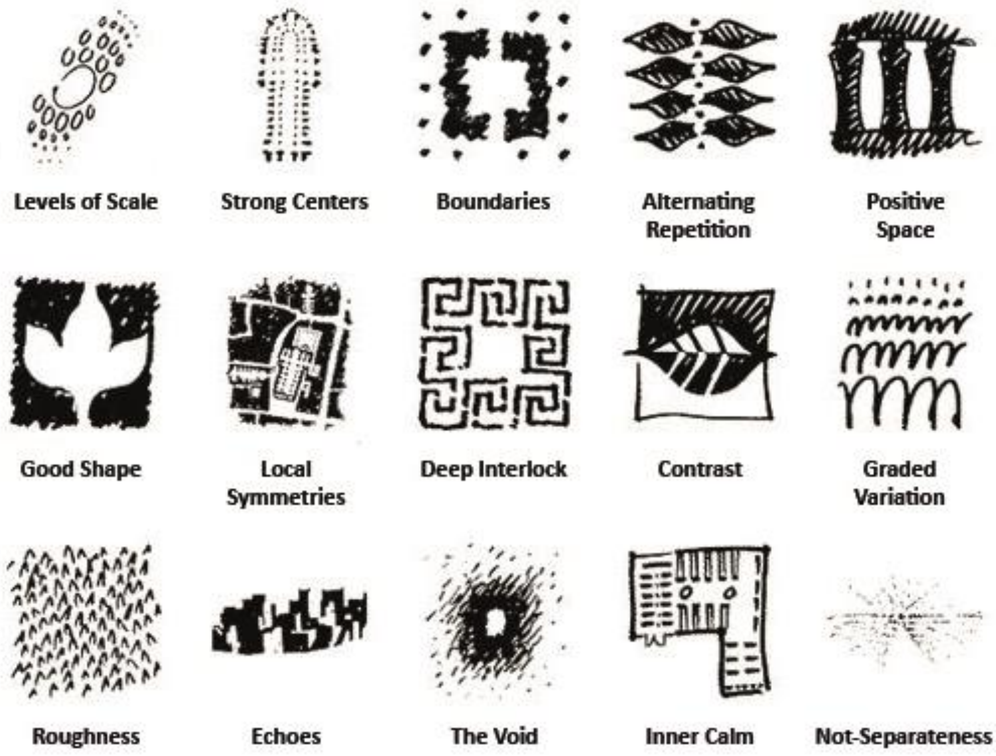


Fig. 42. Principles of *wholeness* from Christopher Alexander's "*A New Theory of Urban Design*" (retrieved from https://it.pinterest.com/).

Alexander's observations entertain some similarity with the idea of an emergent urban form shared by parametric design. Nevertheless, this last point about the *grassroots* source of morphogenesis, together with what we previously said upon the *circular* nature of evolutionary processes, will be crucial for clarifying a right and proper distinction between purely *generative* methods and *parametric* modelling along their staggered overlay fringe.

1.2.4. Towards an hypothetical re-interpretation of space: generative massing as a different interface between designer and modelling dynamics of morphological solutions

Let us add few reflections to the discourse before skipping to the *ut supra* distinction between purely *generative* and *parametric* models. The methodological reformulation proposed by *generative* approaches can be expressed, as we have seen, in more than one speculative direction. To a higher level of abstraction of the speech exposed until now, we can integrate further considerations in line with what has been recalled through the literature, in order to expand the notion of *generativity* in the field of urban massing. We can do this by paying attention to not only the preparation of algorithmic norms and inclusive conditions for in-game stakeholders, but also the way in which we interfere with space during the process of transformation in the most material, technical and compositional sense of the term. Whereas for *compositional* we mean what properly concerns urban design.

Conceptualizing space as the real primitive material of a settlement project is an essential step to appreciate the revolutionary bulk of a *generative* approach to composition. Considering the primordial bond of gravity, movement patterns, the resulting localization schemes of human activities and the need for soldering their respective shells to the ground are all conditions that require the project to exploit space in with ponderation in its three dimensions, prospecting a flexible evolution along the fourth. This need appears dramatized by the framework of consistent urbanization of human presence on our planet (Martine, 2012), the demand for highly performing settlements under morphological, energetic and environmental profiles at both the micro and macro-scale (Duany et al., 2004), and the sharp entropy of lifestyles, use practices and transformation logics in the contemporary urban realm (Basta & Moroni, 2013).

Therefore, it may appear useful to reinterpret the space of any urban transformation project also in the form of an opportunity matrix that describes, in a three-dimensional reference system, a stack of possible morphological alternatives within a given perimeter. Alternatives, we can say, of volumetric articulation in accordance with a socio-technical[62] apparatus of cognitive resources, values and objectives. In a *generative* perspective, the conversion of this apparatus in a system of performance rules prefigures the act of programming an algorithmic procedure that incorporates such norms by outlining in length, height and depth the locus of points able to satisfy them. In other words, the algorithm seeks, among all the potential volumetric articulations that the project may assume, the concatenation of specific three-dimensional coordinates within the spatial reference system described by a transformation area.

A revolutionary change of paradigm follows from this line of reasoning, which revokes nothing but the rise of an *associative dynamic* in the place of a purely *additive dynamic*. In fact, space does not undergo anymore the positive[63] intrusion of a volume by the hands of the designer, but rather a partitioning crevice that allows volumes to emerge from a web of coordinates chosen among all the possible combinations that can be materialized in the reference system. Accessing the control board of the *genetic code* means unlocking the door of a virtually unlimited array of formal layouts, in constant dialogue with the set of organization rules they may ever assume. The compositional result will be anyway bound to a "puzzle box" in which shapes are sorted to order the visible in public space and, by induction, define the accepted density for private space (cf. Huet, 1984).

Such interpretation of the concept of *generativity* in relation to the emergence of volumes can entertain some similarity liaison with the quirky art of a sculptor who, from an entirely amorphous marble block, digs in the matter by approaching more and more to the surface profiles[64] that he desires most. This also happens in a *generative* urban design process by computational means, with the difference that the statue is not shaped by the sculptor manually, but it emerges from an automatically shaved envelope based on algorithmic dissection mechanisms.

[62] In other words, socially constructed through fertile multi-actor interactions, both in vertical and horizontal sense, but also mediated by mastery of technical competencies, which sets up the prerogative of both designers and sectorial experts.

[63] By *positive* we intend here two matching concepts: first, the meaning of "placed from the outside", derived from Hegelian conceptions; second, the meaning of "imposed" for reasons of a supposed rationalization of settlement arrangements under some sort of a technical authority, which draws inspiration from Modernist visions.

[64] Read "*locus* of points".

1.2.5. Parametrics and generativity: distinguishing self-contained and linear *form-finding* routines (*forward design*) from closed *form-finding* cycles of *optimization* (*inverse design*)

Algorithms formulate the genetic principle through which forms manifest their look and behavior. The essence of algorithms as "roadmaps" to the rise of forms makes the focus gravitate from outcome to process of organization, based on instructive series of rules. As such, they are intimately generative devices. Being construction "histories", these generative vessels collect the solutions to an ordered sequence of constraints toward summative results, which are always the unknown variable of the system (Barrios, 2014; Friesen & Vianello, 2014). This framework is not far from what we have said with reference to the self-organized growth of natural structures. In fact, we can interpret parametric form as a substance whose basic constituents develop from the gradual association of primitive elements. The algorithm is no more than the prescriptive rule informing such *self-organization* process[65].

Originally, a parametric diagram represents the "script" for self-organized forms. However, alternative definitions can support some sort of *evolutionary* intelligence too: intelligence expressed through the attainment of adaptive capacity. These two alternative, but non-exclusive ways of constraining the system correspond to two procedural patterns of geometry: the former describes a *linear* process of computation, while the latter consists in a *circular* (or *looped*) process of computation. In both cases, every instance model is deterministically linked to one definite configuration of parametric values, set for single *input* or *container components*, and one precise network of geometric operations, solved by *standard components* and soldered through *wired connections*; the whole set of components, together with relative connections, constitutes the constraint system as a whole. Nevertheless, linear and circular processes differ in how they compute output forms. Within a linear process, that is, the regular version of a parametric algorithm, data flows describe *open cycles* from input to output values in a rigorously left-to-right scheme. The process of computation is a self-contained routine that stops as soon as the output is found (on the right) at every change of parametric values (on the left). Here, directivity is particularly evident. Conversely, a circular process, that is, the generative extension of a parametric algorithm, sews up data flows in *closed cycles*. In this case, computation is not anymore a self-contained routine, but is part of a circumscribing loop that connects every output instance to the recalculation of input values, based on feedback mechanisms (Jabi, 2013) that emulate the adaptive struggle of organic nature. Here, the evident property is not directivity, but recursion, laden with evolutionary character.

Linear and *circular generativity* mirror, respectively, two archetypal styles of parametric manipulation: *forward design* and *inverse design* (Vanegas et al., 2012). As we connect output forms with calculation of performance measures, these two methods become a central discretion of designers in their quest for morpho-efficiency[66]. In fact, forward and inverse modeling denote different patterns of human-machine interaction, which has significant implications for how we relate control of parameters to goals of performance. In both cases, choosing parameters and goals is on behalf of humans, thus we cannot expect machines to suggest suitable constraints[67]. Change can be observed, rather, in the autonomy left to feedback and interference. Forward design consists in handling parametric levers directly and arbitrarily, having target performance in mind and trying to achieve it through a "*fine-tuning*" practice (Beirão et al., 2012) that implies constant supervision of results at every linear

[65] In this way, parametric diagrams assert themselves as tools for managing the complexity of forms, sorting and combining a variety of conditional principles. Their procedural essence may become the key for unlocking dynamic and comparative studies of how diverse variables influence built environmental space, thus suggesting a novel perspective for interpreting and augmenting the phenomenology of masterplans. Steinø (2010) argues that we are experiencing two parallel (but converging) initiatives: both urban design practitioners and the academic world are developing different approaches to parametric modelling, which may downsize the limits of static designs with the introduction of dynamic plans, based on parametric thinking.

[66] Where efficiency stands for correspondence between performance values of a form, which result from a specific configuration of its parameters, and target values.

[67] The only thing machines can do in this respect is signaling correct, warning and error statuses (cf. Tedeschi, 2014).

propagation of data. Professor Alberto Pugnale (2014, p. 359), lecturer in Architectural design at the University of Melbourne, calls this practice of calibration "*form-improvement*", but both terms stand for the same method.

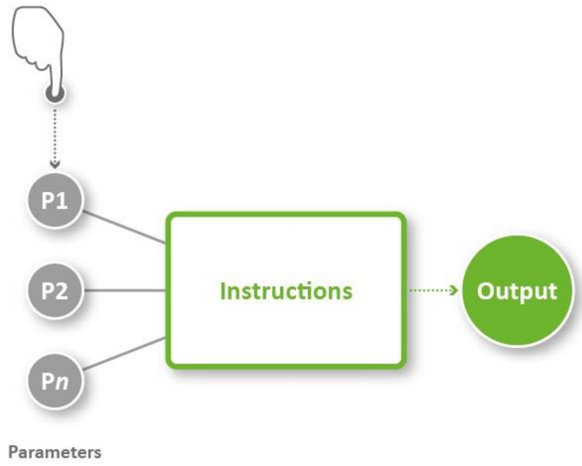


Fig. 43. Schematic representation of *linear generativity* in parametric modeling. This first routine illustrates a *forward design* paradigm, which supports *fine-tuning* practice (elaboration from Tedeschi, 2014).

Instead, inverse design upsets the allocation of autonomy: in fact, it gives the computer a central role in tuning parameters over checks conducted cyclically on predetermined target, which leads to find the most appropriate values only in the end. Reconnecting performance reactions to root parameters means unlocking the automatic recomputation of input settings over and over again, fueling the progression (or the *evolution*) of form toward a known target thanks to trial-and-error moments that persist at every propagation of new data. In one word, boosting not anymore a fine-tuning, but an *optimization* practice. Loosely speaking, inverse design enables one to set a goal and let the machine "do the work", but this does not necessarily entail the objectification of design activity: running optimization is a conscious choice of human elements who take responsibility for the accuracy of constraint systems and the ontology of outcomes.

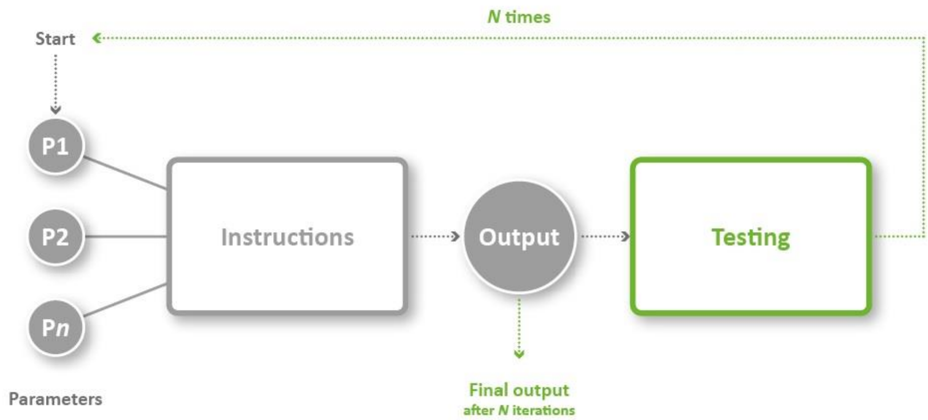


Fig. 44. Schematic representation of *circular generativity* in parametric modeling. This second routine illustrates an *inverse design* paradigm, which supports *optimization* practice (elaboration from Tedeschi, 2014).

Optimization practice performs as the recursive extension of a parametric diagram that, otherwise, would only sustain left-to-right connections. In this sense, solutions are explored stretching guess and check routines to a loop that imitates the principles of natural selection, where a continuous comparison to target skims parametric values and picks their "best" generation, that is, the one adaptive enough to survive and transmit its hereditary characters round after round (Turrin et al., 2011).

Converting the parametric diagram into a recursive loop requires constraining the system with an optimization solver, a special kind of standard component that arbitrates the interplay of input and output values. This solver is of *heuristic* nature: contrary to an *exact* solver, which finds the optimum returning always the same result, a heuristic solver finds an approximate solution when we cannot afford exact solutions, due to the intrinsic complexity of the problem (Tedeschi, 2014). Since architectural and urban problems require managing a conspicuous number of variables, we cannot expect optimization to pick maxima or minima with certainty. Thus, it is our duty to recognize the appropriate solver for a particular problem, which, in this case, is a heuristic one.
Suppose that we translate an optimization problem into visual syntax, such as a basic definition in *Grasshopper*. The problem finds its reason to exist in respect to two indispensable elements: *1*) an *objective function* or *fitness*, which corresponds to the output value we intend to *minimize* or *maximize*, and *2*) one or more variables having at least a partial impact on resulting *fitness*. These variables are, clearly, parameters of the system. In *Grasshopper*, the only input format that supports optimization is the number slider, which means that complex informers like Bézier curves need to be first converted into definitions based on legible levers and detailed knowledge of mathematics (Tedeschi, 2014).
A typical optimization problem is finding the point on a curve that is closest to a separate point *A*. In this very simple example, the *objective* is the function that describes all possible distances between the points belonging to the curve and point *A*, i.e. the output of a standard component measuring the distance between point *A* and the point generated on curve. The only variable is the parameter that governs the point on curve according to a normalized projection between 0 and 1, where 0 and 1 are the extremes related to the end points of the curve. The *optimum* for this problem is the [0; 1] value that minimizes the output distance (Tedeschi, 2014).

Connections between solver and arguments of optimization invert the left-to-right sequence we find in *linear* generativity: in fact, wires are dragged starting from the solver and heading to parameters and fitness. Double-clicking the solver is essential for opening contextual settings and selecting options of maximization and minimization. In the example, the distance function is optimized for the minimum output[68]. Other very important options concern the management of complexity. Optimization can be based, in fact, on two "scales": *local* and *global algorithms* (Tedeschi, 2014). In brief, local algorithms search for exact (or heuristic) optimality limited to the neighborhood of starting values. On the contrary, global algorithms inspect all possible values of input. Tedeschi (2014, p. 434) suggests that it is often useful to run first a global, and then a local algorithm in case of very complex problems.
The example of points on curve served a general understanding of the main elements partaking in optimization problems. Specifically, finding the "right" point for such a simple definition would only require an exact solver like *Goat*, a plugin for *Grasshopper* developed by the Viennese mathematician Simon Flöry[69]. Yet, what tickles our fancy is how a heuristic solver can relate to the optimization of much more complex systems, such as urban patterns. Our compositional problem becomes a top dilemma for heuristic optimization, as we notice that even apparently trivial issues, like finding the shortest path between two ends on a freeform surface, cannot be solved through the exact approach. In these cases, it is necessary to exclude *Goat* in favor of *Galapagos*, a well-known plugin for *Grasshopper* developed by programmer David Rutten. Rutten is also a central figure for the implementation of *Grasshopper* itself (Tedeschi, 2014). *Galapagos* best incarnates the principles of evolution in relation to problem solving, selecting candidate "*genes*" (values) by digital emulation of nature. Candidates attempt to ripen better genetic characters according to given fitness, fielding stratagems like mutations, crossovers and random changes that resemble the typical progression of DNA structures over eons of time.

[68] Alternatively, both exact and heuristic solvers are compatible with the concept of target values for objective functions. The stratagem consists in using two simple math components in combination: a calculator of differences and a converter into absolute values. The role of fitness relates not anymore to the actual indicator, but to the absolute value of its difference from a fixed number, that is, the target we need to attract or repel (Tedeschi, 2014).
[69] *Goat* components can be found at http://www.food4rhino.com/, while some applications are available at http://www.rechenraum.com/en/.

PART 2 ANALOG AND DIGITAL PARAMETRICS

From *analog form-finding* experiences to the *digital* complexification of modeling: the evolution of constraint systems toward generalized parametric options

1.3. The analog origins of parametric design: the first historical finalizations to highly performing morphologies, in search for structural optimality

1.3.2. *Analog* parametric design: figuring performing design solutions by means of natural and default systems of constraints, derived from the experience of physical world

Reconstructing the evolution of parametrics across major historical experiences has been an essential step for acknowledging the cultural debts of actual state of the art. In particular, our point of view adopted the explicit reference to gradual sophistications in managing ever-higher complexity of forms, for urban dimensions expect appropriate magnitude of control.
The examination of literature suggested a selection of fundamental stages, hallmark authors and applications. Due to redundant information, here we put aside the mathematical origins of parametric formulas, referencing Dana (1837) and Davis (2013) for details. The original manifestation of parametric design as a support system for predisposing form has been carried out through analog technology (Davis, 2013; Woodbury, 2010). *Analog parametric design* was grounded on the *material computation* of outcomes, based on extensive use of physical models. These models, namely maquettes or manual procedures of calculation, embedded forces of nature and principles of empirical reality as constraint systems. In this sense, they involved "*natural algorithms*" describing predefined and immutable instructions: something bypassing *fine-tuning* to achieve the upfront *optimization* of design. Forms could not but reach direct optimality, because those instructions made them sensitive to the generative spirit of nature. However, principles enacting natural algorithms were generally mono-parametric, i.e. subject to single forces such as gravity (Tedeschi, 2014), which contained their range of application.
As models stack to physical world, they led to the generation of three-dimensional forms. This passage has not been as direct in the first *digital* applications and should not be considered as a minor aspect. Spatial obstructions propagate across at least three dimensions in complex environments like cities. However, material computation could not but deal with strong difficulties in terms of both availability and replicability of instruments. Also, costly methodologies and maquettes denied any facilitation for structures beyond a certain threshold of complexity.
In pure mathematics, a parametric equation expresses a set of quantities as explicit functions of a number of independent parameters. Material computation was able to reproduce arrays of outcome forms in pretty much the same way, grounding variation on the arbitrary change of independent parameters, and both correlation and evaluation on natural algorithms, which performed as the basis of geometric associations.
With reference to *analog* parametrics, we considered discussing three milestones: the Spanish Antoni Gaudí, the Italian Luigi Moretti, and the German Frei Otto. Each of the three architects endorsed different and unique approaches to the material computation of optimal structures, each with its own pattern of variation, correlation and evaluation. Gaudí practiced what we recognize as the first systematic experimentation of parametrics for architecture, in the late XIX century. Specifically, he used gravity as a solver for optimal parametric arches and vaults. Instead, Otto represented the ultimate development of analog parametrics, starting from the interpretation of chemical bonds as innately predisposed to *minimum energy*.
Unlike the other two protagonists of this chapter, Moretti did not make use of any physical model and resorted, instead, to hand-made calculations of optimal profiles. Material computation of such profiles is what primarily characterizes Moretti as a figure of analog parametrics. Yet, it is important to note that his own manual computation of outcomes already represented a step beyond, compared to the other two examples. In fact, this kind of approach let him constraining form through a *custom* and even dual principle, leading to a compound and multi-parametric definition for the first time. This anticipated by far the personalization of parametric conditions, which, based on *virtual algorithms*, has been carried out only few decades later, placing not "imposed", but "wanted" rules at the core.

1.3.2.1. Antoni Gaudí in the late XIX century: the application of classical mechanics laws to the design of load-bearing architectural structures, by means of *hanging chains*

Gaudí's background curriculum included a strong knowledge of advanced mathematics, general physics, natural science and descriptive geometry (Davis, 2013). Given such premise, it probably could not abstain from pervading the inherent character of his own architecture. An evidence of how deeply Gaudí understood mathematics resides in the consistent recourse to mathematically ruled surfaces, such as helicoids, paraboloids, and hyperboloids, which were then infused into *associative* connections with ruled lines, Booleans, ratios and catenary curves (Burry, 2011; Davis, 2013). Although he could ignore the earlier works in defining parametrically related geometries, Gaudí actually employed models underpinned by parametric equations when designing his stunning architectures[70].

Despite not the only one, the brightest example of parametric architecture boasting Gaudí's signature consists perhaps in his design for the Colònia Güell Chapel in Barcelona (*figs.* X and Y). Aside from the aesthetic detail, which is only an outward consequence of parametric factors, what should capture our attention is, rather, the mechanical manifestation of shape.

Fig. 45. A couple of photographs showing the crypt of Colònia Güell chapel by Gaudí (retrieved from: http://www.gaudicoloniaguell.org/).

The religious structure has been generated through a *hanging chain model* (Burry, 2011), whose rationale laid out the underlying parametric diagram by acting as a natural algorithm. Springing from one of Robert Hooke's (1635-1703) intuitions, the hanging chain model is grounded in a gravity-based parallelism that links a hanging chain, which forms a *catenary curve* in *tension* under its own weight, and an arch, which stands in *compression* (DeJong & Ochsendorf, 2006). More specifically, the shape a string assumes under the *tension* of a set of loads, once rigidified and inverted, describes a path of *compression* forces for an arch to support the same set of loads. The shape of both the string and the relative arch takes the name of *funicular* shape for these loads (DeJong & Ochsendorf, 2006).

Hooke could not derive the equation of a catenary curve. However, despite the lack of an accurate formalization, he felt that his intuition about the *associative* link between the *tension* of the curve and the *compression* of its mirroring arch was right. He somehow knew that hanging a string naturally created a catenary in equilibrium, which distributed gravity loads in tension. If inverted, that same shape could perfectly distribute equal loads in compression. Thus, he wrote his finding as an anagram to be deciphered in Latin (Hooke, 1675, quoted in DeJong & Ochsendorf, 2006):

[70] In this respect, Davis (2013) argues that it is not possible to know whether Gaudí was directly influenced by scientists and mathematicians who had earlier used parametric equations to define geometry. Similarly, Mark Burry (2007, p. 11), the current executive architect in charge of the Sagrada Família, says there is "*virtually nothing written by Gaudí himself about the motivations, theories and practice that pushed him to stretch the limits*".

«abcccddeeeeefggiiiiiiiiillmmmmnnnnooprrssstttttuuuuuuuuu»[71]

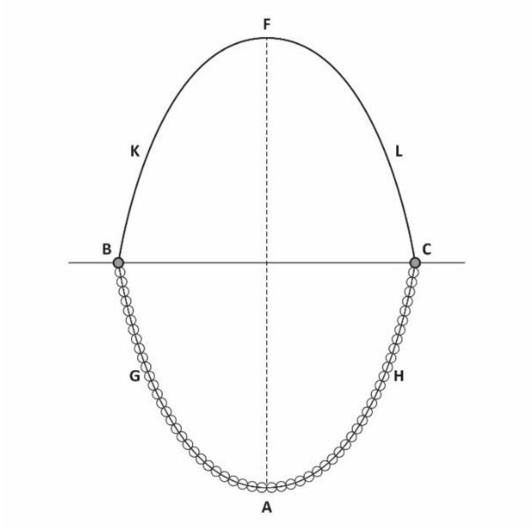


Fig. 46. A schematic representation of a hanging chain forming a catenary (bottom) and the corresponding arch (top); given $\overline{BC}$ the width and $\widehat{BC}$ the length of the chain, the point *F*, which stands in compression, supports the same load that *A* bears in tension (elaboration from DeJong & Ochsendorf, 2006).

The expression, once decrypted and translated from Latin[72], stands for:

«As hangs the flexible line, so but inverted will stand the rigid arch» (DeJong & Ochsendorf, 2006, p. 2).

The hidden meaning of Hooke's anagram soundly inspired the *associative* model applied by Gaudí for Colònia Güell. In order to discipline the emergent behavior of the chapel, the architect reproduced this self-adjustment principle with an inverted model (*fig.* X), using strings weighed down with birdshot (Davis, 2013). Meanwhile, the intuition that an optimal arch reflects an inverted *catenary curve*, that is, a hanging chain, had already been proved by precursory experiments on existing structures[73].
Taking into account the means of his time, Gaudí's "upside-down" physical model took him years to build, but gave him the opportunity to explore organic designs with a relatively high level of flexibility, due to the inherently *autopoietic* nature of the system. This is because every manipulation of string length, point location and applied loading would instantly trigger an analog (but automatic) re-computation of optimal arches. The three parameters had a determining effect on final geometries: the outcome curve could change in terms of span/rise ratio and distribution of loads in tension, through point loads and suspension points, but always ending up as a structurally optimal arch once in compression (Pugnale, 2014).

[71] Hooke, 1675, p. 31, retrieved from: http://www.danieldavis.com/.
[72] *«Ut pendet continuum flexile, sic stabit contiguum rigidum inversum»* (DeJong & Ochsendorf, 2006, p. 10).
[73] We can quote an interesting passage from DeJong & Ochsendorf (2006, p. 10), narrating the experiment conducted by Giovanni Poleni (1683-1761), using Hooke's principle as a tester for appraising the load-bearing performance of St. Peter's cathedral: *«In 1748, Poleni analyzed a real structure using Hooke's idea to assess the safety of the cracked dome of St. Peter's in Rome. Poleni showed that the dome was safe by employing the hanging chain principle. For this, he divided the dome in slices and hung 32 unequal weights proportional to the weight of corresponding sections of that "arch" wedge, and then showed that the hanging chain could fit within the section of the arch. If a line of force can be found that lies everywhere within the masonry, then the structure can be shown to be safe for that set of loads».*

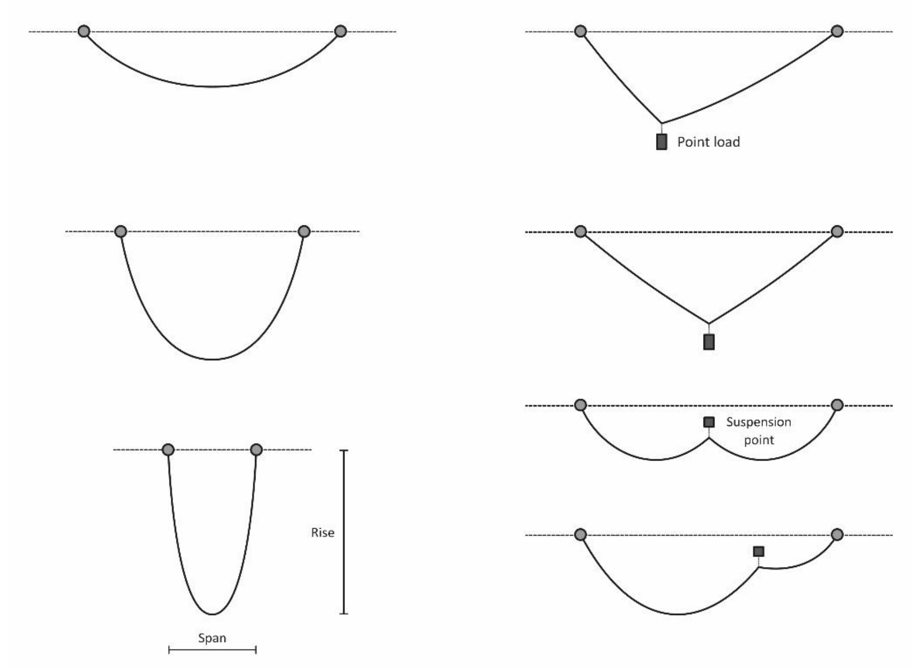


Fig. 47. Variations of parametric inputs and corresponding catenaries: we observe different configurations of rise/span ratios (on the left) and applied loading (on the right), through the introduction either or both point loads and suspension points (elaboration from Pugnale, 2014).

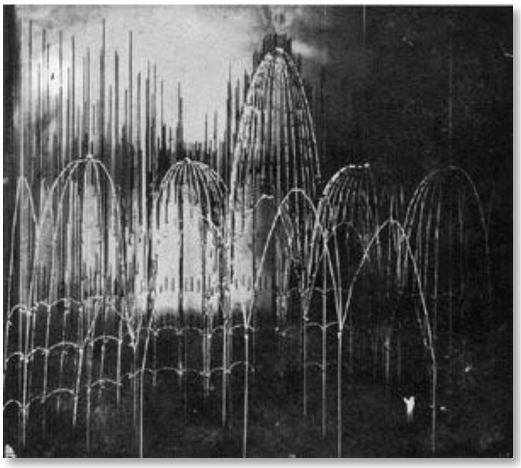


Fig. 48. Two instances of the *hanging chain model*: on the left, the reconstruction of a battery of *catenary curves* attached to a plate; on the right, an rigidified and inverted catenary, resulting in a group of *optimized arches* for specific widths, lengths and weights (retrieved from: https://it.pinterest.com/).

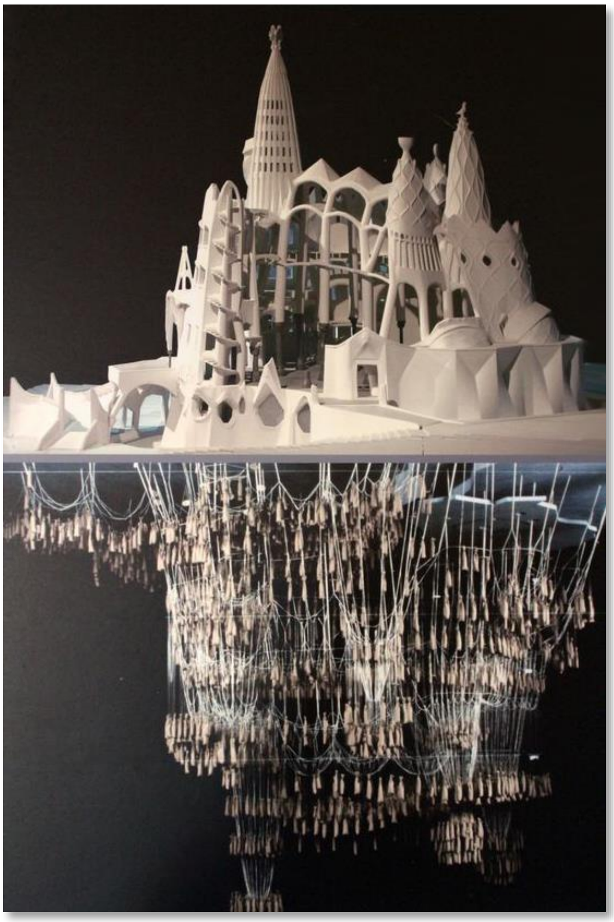


Fig. 49. The *hanging chain model* implemented for the Colònia Güell chapel: the model at the top, which surely boasts a more familiar aspect, has been derived from the several catenaries we see at the bottom, which acted as an underlying parametric matrix of load-bearing configurations (retrieved from: https://it.pinterest.com/).

The *hanging chain model* can be considered as a parametric system at all effects, with all the algorithmic factors and logics we have already seen before. In fact, we find: *1*) a set of independent *parameters*, which in this case are string length, anchor point location and birdshot weight; *2*) a system of *constraint* expressions or explicit functions, which in this model reflects the laws of Newtonian motion; and *3*) an array of (*responsive*) outcomes, which correspond to the various vertex locations of points on the strings, resulting from the constraint system of classical physics.
This natural algorithm runs in such a way that the strings would always settle into a shape that, once inverted, would mechanically stand in pure compression, whatever their starting settings. By modifying the independent parameters of his parametric model, Gaudí could generate versions of the Colònia Güell Chapel and be assured of the autopoietic routine performed by resulting structures, thanks to the injection of natural instructions into physical modeling.
Since Gaudí's model was geared to tentative changes in parametric inputs, a property that clearly foregrounded the exploratory nature of this "upside-down" approach, we could appreciate practicing with this analog, *fin-de-siècle* model as a *form-finding* experience ahead of its time. And an automatic one of that. Gaudí marked an important step beyond the earlier use of parametric equations by mathematicians. In fact, through the natural algorithm of Hooke's principle, the system could compute the parametric outcome according to the embedded automatization of the model, with no need to calculate the formula of catenary curves at each modification of

input data (Davis, 2013). Instead, the architect could automatically derive the shape of catenary curves through the sole force of gravity acting on strings[74].
Gaudí's experience left us the opportunity to explore the emergent behavior of form in a facilitated way, without ungluing the design quest from a "conditioned" way of modeling, which helped granting structurally sound shapes by means of a frugal, yet ingenious mechanism. In this sense, the model stuck to a diffused parametric design "dogma" among architects, which confers a utilitarian emphasis on exploring the automated possibilities offered by the model (Davis, 2013). Despite the use of a physical model, the essence of parametric properties, especially with reference to algorithms-aided design, does not change: acting as a *form-finding* matrix, the analog model yields a set of outcomes expressed as an explicit function of a number of independent parameters.

1.3.2.2. Luigi Moretti in the 1940s: the calculation of "*equi-desirability curves*" as tools for finding optimal architectures, in terms of visual angles and construction costs

Despite the experimental injection of parametric systems into new architectures has been launched by Antoni Gaudí, who surely made a permanent impression on architecture history, the first caption that combined the term "*parametric*" with its design-oriented finalization has to be credited to the Italian architect Luigi Moretti (Davis, 2013).
Through an introductive section, we have already given a hint about Moretti's "borderline" role in the development of a toolbox for parametric design. Although this figure was largely devoted to *analog form-finding* models, we could credit Moretti with predicting the achievements that have been assimilated to *digital* devices. In fact, with reference to the study of performance implications based on constraints, Moretti has been a cardinal turning point due, on the one hand, to his extensive recognition of computational developments as powerful innovators for design practice, and, on the other, to the crafty involvement of more than one single constraint criterion into *form-finding* procedures.
Precisely, the architect invented the definition for "*parametric architecture*" in 1939 (Tedeschi, 2014), during years of consistent epistemological speculations for modern-era design discipline. In his view, a truly "modern" architecture should not be called as such for belonging, banally, to the space-time setting of "modern times", but rather for its revolutionary endorsement of novel dimensional relationships, based on precise mathematical reasoning. In other words, for its sound ambition to rethink form as the "unknown variable" of a complex equation, in which a certain number of factors, namely *parameters*, comes into play according to seminal designerly choices (Galli, 2011).
To Moretti, the goal of this new architecture consisted, indeed, in the arrangement of a bounding box of formal solutions, rising from given parameters and constraints: both of these had to be chosen in response to a desirable performance, or an equation to be verified, instead of exasperating the motionless articulation of accustomed, standard shapes to solve diversified problems. The process of abstraction of form instances, which constitutes the very basis of parametric diagramming, is what deeply characterized this philosophy. In Moretti, the essence of architectural discipline resides, more than in its executive values, in an abstract matrix of structures, springing from the complex relationships through which forces and principles of mathematics govern spatial properties[75]. In this sense, conceiving a parametric architecture becomes a key to access a sort of *topos hyperuranios* of form, deriving single instances from a generalized "cradle" of geometries.

[74] This method of analog computing has been furtherly developed by Frei Otto to include, among other things, minimal surfaces derived from soap films and minimal paths found through wool dipped in liquid. Taking place in the 1990s, these experiences represent the ultimate achievements of *analog parametric design* and we will discuss them in two sections.
[75] This interpretation of architecture gathered its mathematical background from the famous "*seven pages*" that Évariste Galois (1811-1823) wrote in the desperate attempt to sort out his theory the night before a fatal honor duel with his rival. Galois's final intuitions, although cryptic due to (tragic) time restrictions, revealed to Moretti that the world was the image of pure and dynamic relationships, independently from the static and superficial appearance of things themselves (Bucci & Mulazzani, 2002).

The Twelfth Milan Triennial of 1960 represented a chance for Moretti to display the results of his morphogenetic research, showing how novel forms could be generated from the active interplay of parameters based, in turn, on selected constraint expressions. His "*Parametric Architecture*" exhibition presented versions of parametric stadiums for soccer, tennis and swimming (Tedeschi, 2014). Moretti derived the shape of these stadiums by factoring two performance constraints in the equation: visual quality and economic cost of concrete, which were calculated per each increment in both viewing angles and elevation levels of bleachers around the playing field (Davis, 2013). In search of an efficient shape per each point, the architect chained the result of every local calculation within a sequence of what he called "*equi-desirability curves*", i.e. proto-isocurves that attempted to describe the *locus* of optimal views from every location (Galli, 2011). Playing as the unknown term of the equation, the shape of each stadium stemmed from the plastic envelope of these isocurves, developing architectural components in a vertical sense.
This double-sided system of constraints, based on both visual quality and economic feasibility, led the architect to plot a *multi-parametric form-finding* routine well before the dawn of digital algorithms, despite simply relying on manual calculations and outlines. Even more importantly, both constraints described *user-defined* expressions for the first time, with no need to sustain the model by means of natural instructions such as gravity principles in Gaudí's hanging chain solvers.

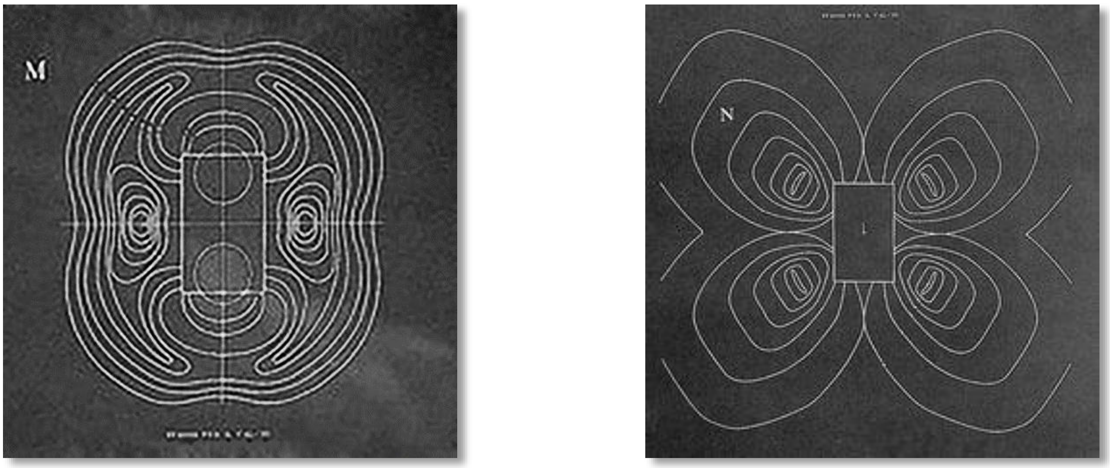


Fig. 50. Moretti's hand-written plans for two stadium models, *M* and *N*, showing the *equi-desirability curves* that regulated the emergence of morphological profiles, with reference to visibility and economic costs per viewing angle and elevation height (retrieved from: http://www.danieldavis.com/).

Fig. 51. One of Moretti's models of stadium, exhibited at the 1960 "*Parametric Architecture*" exhibition at the Twelfth Milan Triennial. On the left, the plan with its corresponding curves; on the right, the resulting three-dimensional model (retrieved from: http://marcolucci.altervista.org/).

Moretti's interest in a pervasive mathematical scope for design was not an orphan feature of his philosophy. In fact, the architect held his research in collaboration with a well-known Italian mathematician, Bruno De Finetti (1906-1985), wherewith he founded the *Institute for Mathematical and Operative Research in Architecture and Planning*, in 1957 (Tedeschi, 2014). Together with De Finetti, Moretti appreciated the potential of mating parametric *form-finding* with the massive use of computers, tools that would soon have reformed the fabrication rules of architectural and urban forms:

> *«The parameters and their relationships become [...] the code of the new architectural language, the "structure" in the original sense of the word [...]. The setting of parameters and their relation must be supported by the techniques and tools offered by the most current sciences, in particular by logics, mathematics [...] and computers. Computers give the possibility to express parameters and their relations through a set of (self-correcting) routines»* (Moretti quoted in Tedeschi, 2014, p. 20).

Despite the *analog* genesis of his models, we can notice that Moretti foresaw the potentials of computing technologies for architecture at the earliest stages of digital boards: actually, the first *Computer-Aided Design* (CAD) application occurred only in 1963 with *Sketchpad*, a pioneer graphical communication system for the development of *digital* parametric design. Quite surprisingly, the label "CAD" has been matched with the simple digital extension of an *additive* design approach, regardless of its parametric and *associative* origins. Moretti himself, although generally recognized as a key figure of 20^{th}-century Italian architecture, seems to be scarcely discussed as a pioneer of computational design, even by architects who today use computers to generate parametric models (Davis, 2013).

1.3.2.3. Frei Otto in the 1960s: the refinement of analog parametric modeling through chemical *form-finding* of minimal architectural surfaces and minimal urban grids

We can credit the German architect Frei Otto with one of the most brilliant visionary minds of the last century. His unconventional contribution to the discipline has gone way beyond mere construction, in a unique attempt to bridge original, science-based techniques with an erudite sense of architecture as art and philosophy (Drew, 1976). In particular, this liaison was grounded in biochemical forces as sources of self-organized forms, resulting from the astounding growth processes of natural systems (Schumacher, 2010). The *generative* essence of nature was, indeed, a central concern for Frei Otto in relation to the structural performance of his architectures. In his view, forms rising from natural laws could never be considered as chaotic: they represented, rather, the product of a complex molecular optimization in the course of time, where the outward aspect was an unknown variable of the process. Drawing from such notion of nature as an optimizing agent of form, Otto came up with the intuition that its secret order would have mirrored the spontaneous reproduction of *minimum energy* patterns (Lopes et al., 2014). Le Corbusier (1987) had already realized that although:

> *«nature presents itself to us as a chaos [...] the spirit which animates Nature is a spirit of order»* (Le Corbusier, 1987, p. 18).

Nevertheless, his understanding of such "*spirit of order*" was limited by the science of his day. Conversely, the German architect analyzed in depth the underlying rationality of natural systems in the following decades, with specific attention to their performative power. In fact, Frei Otto grasped the complex order of those apparently chaotic shapes by achieving their material computation with original parametric expedients. Contrasting Corbusian defects, Patrick Schumacher (2010), a top advocate of parametric design, argues that Otto's sensibility:

> *«gives more credit to the hidden order of apparently chaotic layouts as a form of recursive material computation than to the simplicity of clear geometries that can be imposed in one sweeping move»* (Schumacher, 2010, p. 18).

By means of *analog* models of material computation, Otto prospected the full transposition of natural optimization mechanisms to the artificial arrangement of architectural solutions. Aside from being outcomes of *form-finding* explorations instead of *form-making* traditions, these solutions would have been the vibrant expression of frugal energy consumption channels, reflecting the inborn intelligence of nature.
The replication of such intelligence within building technology has been a central research goal of the *Institute for Lightweight Structures* (*IL*) in Stuttgart, an experimental laboratory where Otto, as a leading figure, concretized his fundamental thought upon nature-driven *form-finding* between the 1960s and the 1980s (Lopes et al., 2014). The inspiration to organic growth processes has been, clearly, a straight consequence of the subject areas that *IL* involved in its frontline cross-sector effort, gathering biologists, anthropologists, geneticists, mathematicians and geodesists in the establishment of a new architectural concept. The idea of a "*lightweight*" technology of architecture, being derived from natural wisdom, would have spurred from the efficient use of materials, leading to designs that would have been not only frugal, but also appealing and functional, due to their organic optimality (Schumacher, 2010).
The concept of lightweight architecture, which stems from a precise *form-finding* research, has been actualized through the investigation of minimal occupation in terms of areal surfaces and linear pathways. Otto associated an architectural sphere to the former category, which would have produced the slightest sweeps among given curves, and a planning sphere to the latter, leading to the shortest routes linking arbitrary point locations (Otto, 2003).
Among the various *analog* parametric devices developed at *IL*, the *soap film model* is probably the most ingenious, yet sparing application of a natural algorithm. Otto conducted a series of vanguard experiments with soap bubbles, a substance that he re-interpreted as a powerful computational tool, due to its chemical properties. In fact, soap films share a *tensile* behavior that minimizes their surface area given a boundary in three dimensions (Lopes et al., 2014). In other words, they are mathematically defined as "minimal surfaces" (Pugnale, 2014). In 1961, his first experiment with suds consisted in plunging a round string in a suspended soap film (*fig.* X). By pulling the string out, Otto observed the natural generation of a minimal surface at every move in both vertical and horizontal directions, thanks to the special tension of the bubble. Taking this episode as a starting point, Otto put more and more complex string borders to the test, spotting the constant adaptation of tensile behaviors and the parallel regeneration of optimal shapes. For instance, Bach (1988), Otto's colleague at the *Institute for Lightweight*, observed an incremental complexification of bordering options, from two round frames, which spontaneously formed a *catenoid*[76], to a single, but intricate closed edge, which gave birth to the so-called *saddle shapes* (Pugnale, 2014, p. 356), as we can see in *figure* X.
Otto's inaugural experiment followed nothing more than the rationale of a *natural algorithm*, highlighting its *responsive* property at each parametric variation. Every outline of borders stood for a different input geometry, developed along three dimensions, while the tensile harmony of soap bubbles served as an explicit, instructive and constraining ruleset for generating a deterministic output surface, sensitive to each particular margin. Interestingly, algorithms based on the self-organization of nature achieve optimality running only once, meaning that they "internalize" *circular generativity* within an automatic and *linear* process, which is quite convenient for human elements[77].

[76] A *catenoid* is the surface of revolution of a *catenary curve* (Pugnale, 2014).
[77] However, the general payoff for designers should also take into account both time and money needed to construct such sophisticated analog devices, as well as the strong limitations in terms of variety of objective functions: for example, Otto's model cannot compute but minimal surfaces, as the inherent nature of soap bubbles only serves that specific purpose.

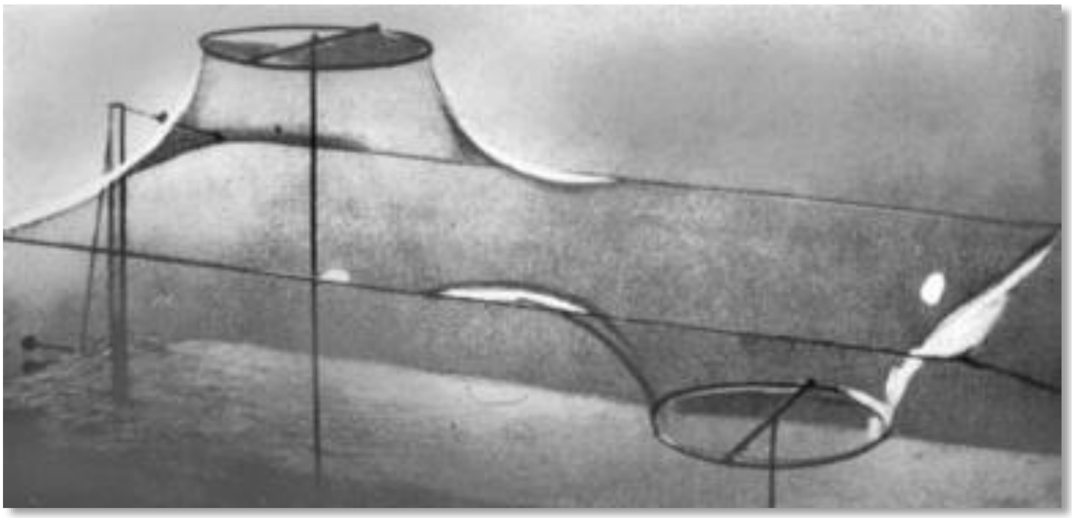


Fig. 52. An image of the famous *form-finding* experiment with the generation of minimal surfaces by means of a simple soap film (retrieved from: https://it.pinterest.com/).

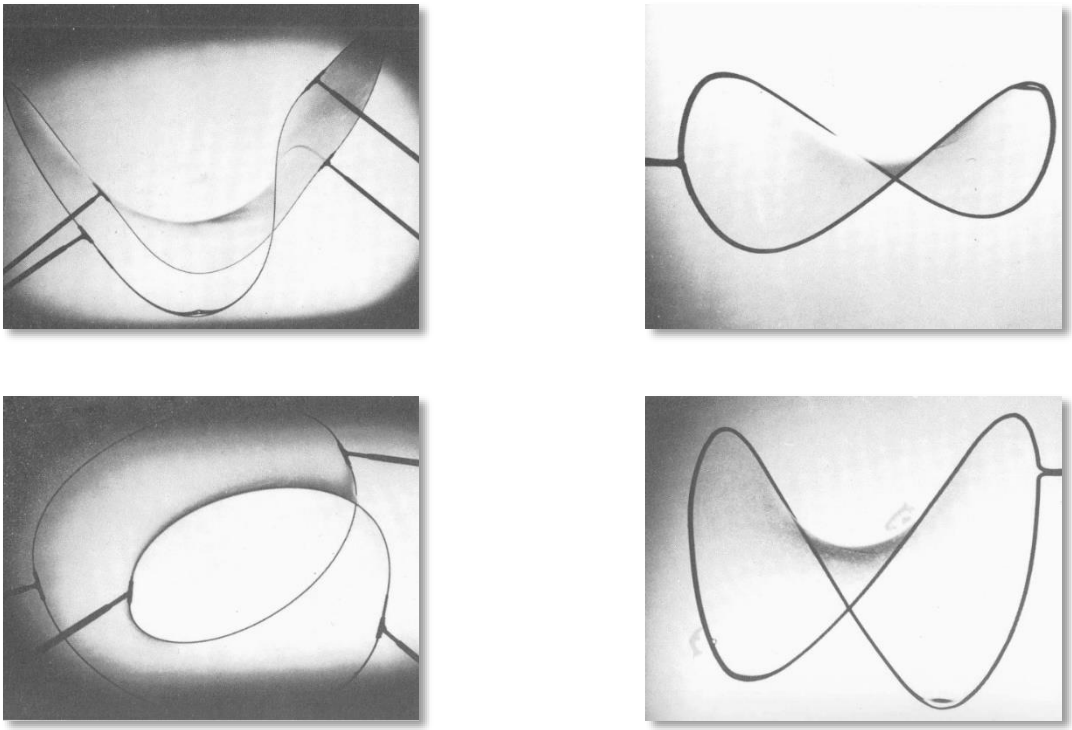


Fig. 53. Some examples of borders showing greater articulation across the 3D space, together with the *responsive* adaptation of soap films; Otto labeled these *form-finding* products as *saddle shapes* (retrieved from: https://it.pinterest.com/)

The soap film method served as an early, but essential explanatory model for grafting natural frugality into the ontology of design: as such, Otto took advantage from it as an operational support for valuing the reliability of its natural algorithm. From his viewpoint, the active assimilation of this kind of *form-finding* could have led to constructions able to run less counter to nature, in a quixotic perspective of conscious learning, technological transfer and mutual integration between what both bio and technosphere had to offer the world.
At the same time, the model was compliant with what Otto considered to be the fundamental self-organization principle observable in the real world. During his experience at *IL*, the architect came to profess a clear generalization of behavioral patterns for physical matter, based on the core distinction between *occupation* and *connection* propensity (Otto, 2003). According to the architect, these two processes perform a spontaneous correlation: while the former takes up space across its different dimensions, from points to volumes, the latter rises

as a consequence of recurrent, overlying and intersecting settlement of geometry. This being the case, the reproduction of complexity takes place as a consecutive chain of geometries from elementary to aggregate arrays. For example, points of occupation spawn paths; in turn, paths generate a linear occupation, in view of a surface connection[78]. Actually, the relationship between occupation and connection patterns is evident in the soap film model too: the method consists in the linear occupation of a surface by means of a looped string; after moving the ring out of the film, the substance restores the connection with a surface conformed to new linear occupation borders.

Since occupation and connection describe two complementary trends of complexification, the cumulation of occupying patterns correlates with the continuous differentiation of connecting networks. In terms of connection, the product of self-organization combines linear segments with an increasing number of forks and crossing points of different *grade*[79]. In other words, these forking systems eventually close into continuous networks as the inexorable "negative" of progressive occupation tendencies (Schumacher, 2010).

The promising results of the soap film model inspired a second declination, this time focused on the economization of linear network layouts. The *Institute for Lightweight* devised the repartition of optimal networks into three categories, namely: *direct path systems*, *minimal path systems* and *minimized detour path systems* (Lopes et al., 2014). Given an either arbitrary or random set of point locations, the goal was finding a network geometry able to minimize their average in-between distance. The first path system served as a theoretical idealization in which every pair of points was joined by one Euclidean line, with no detour options. Clearly, this partial solution did not take into account the overall access to the full battery of alternative locations. An optimal network would have shared, rather, a geometry of junctions and bifurcations arranged as a compromise including more than two points at once.

Starting from this ideal layout, Otto imagined the consistency of soap films as a platform for the self-organization of optimal networks. In this case, the architect reproduced a soap bubble "skin" apparatus made of three main elements: a glass plate held over a soapy water surface, a blower surrounding the tank and a set of needles fixed with tie-rods (Schumacher, 2010). The blowing machine assured the uniform generation of a convex soap wave from every side of the tank. Once the wave bumped into needles, Otto observed its chemical breakdown into a number of concave waves, heading gradually to the joint cohesion of their membranes. The equilibrium point, reached with the sudden stasis of liquids, portrayed this self-organized arrangement of skins as the spontaneous formulation of a minimal path system, which finally satisfied the coincidental join of multiple locations along the shortest route.

Frei Otto's minimal path system represented the solution of a *rectilinear Steiner tree* (Zhou, 2008). As a result of the mutual compression of soap waves, the system spawned additional points, namely *Steiner points*, wherever a detour would have reduced the total distance. Within the minimal path system, Steiner points are clearly recognizable for two common properties: first, they are always nodes with three edges; second, their edges form 120° angles. As we can notice from the following pictures (*figs.* W, X, Y, Z), the minimal path systems developed at *IL* considered needles to be the anchor locations of an open network, meaning that an imaginary agent, once reached a terminus along the shortest route, could not do without turning back to other locations through the same way. In other words, Otto's minimal path system could not embrace the generation of optimal loops as a marginal alternative to otherwise inevitable route choices.

[78] This actually depicts a strong parallelism between Otto's self-organized order and the process of incremental aggregation of geometric primitives we have seen with *digital* node diagrams, which happens to be the "disemboweled" emulation of the same process we find in nature.

[79] By *grade*, we mean a basic centrality measure for classifying a node, which consists in the number of edges it is connected to (Porta & Latora, 2007).

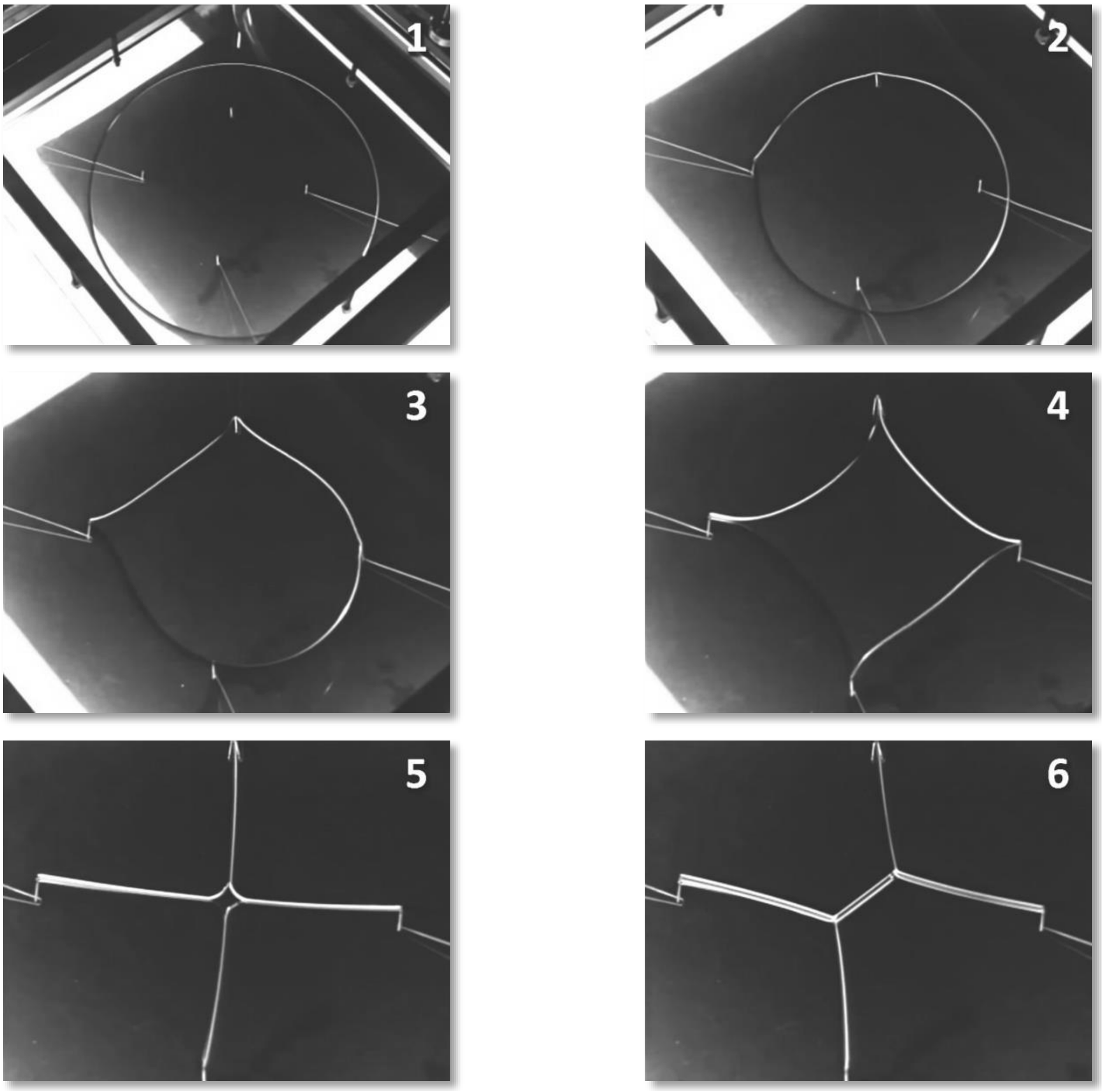


Fig. 54. A sequence taped at *IL* in the 1960s, showing the progressive development of a *minimal path system* through the spontaneous coincidence of soap films, based on a set of input needles; in the last shot, we can notice the self-organized emergence of two *Steiner points* (retrieved from: https://www.youtube.com/).

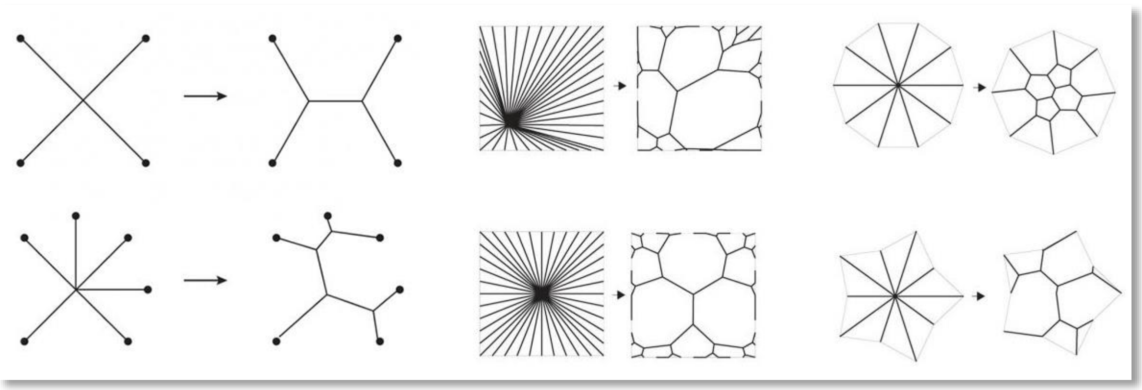


Fig. 55. Schemes contrasting the hypothesis of a *direct path* with an altogether minimization of in-between distances, namely the *minimal path system*, considering the whole battery of point locations at once; based on the specific distribution of points, *Steiner points* always denote strategic locations for detours to minimize average distances (retrieved from: http://www.henn.com/).

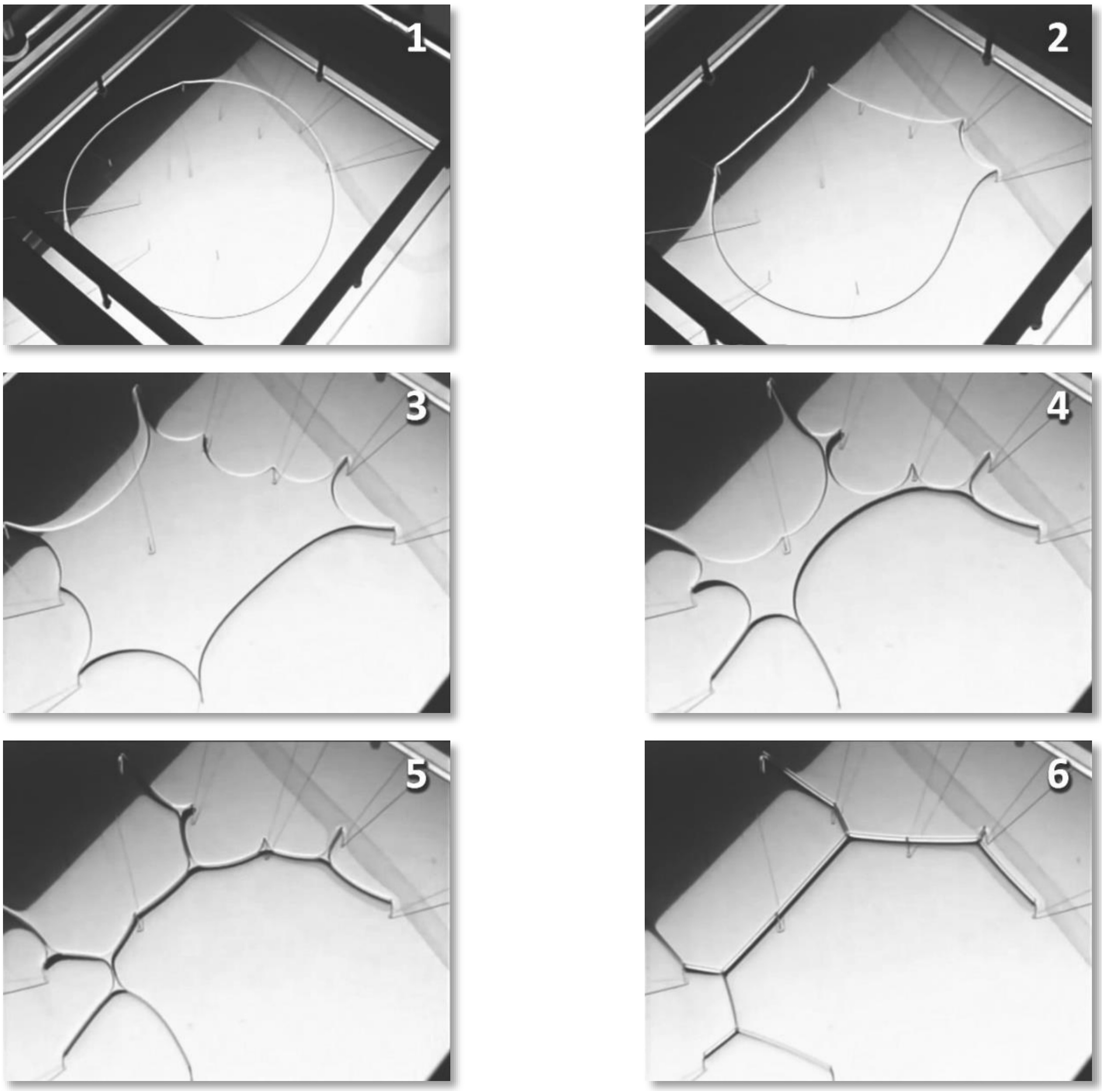


Fig. 56. Another sequence taped at *IL* in the 1960s, this time showing a less elementary distribution of needles, with, again, a number of *Steiner points* emerging accordingly (retrieved from: https://www.youtube.com/).

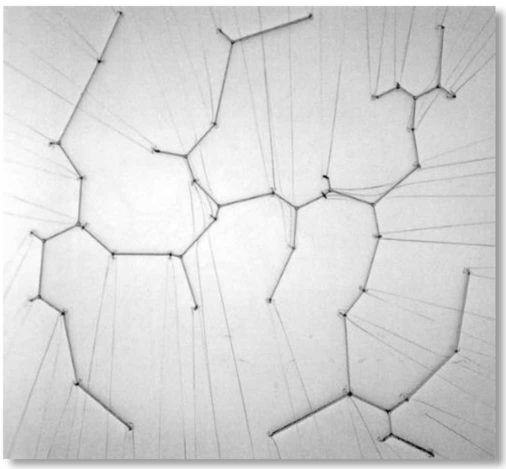


Fig. 57. An example of more complex minimal path systems, rising from a different pattern of needles, in terms of both quantity and dispersion; note that the outcome of this *form-finding* process is always a network embracing every point on one occasion (retrieved from: http://www.patrikschumacher.com/).

Before presenting the third category of path systems, we can stress another limit of Steiner trees with reference to the qualitative articulation of the network. The reflex introduction of Steiner points, needed for minimizing the average spans among various anchor vertices, raised an exponential blooming of ramifications, which led, by contrast, to a number of pronounced swerves in the crossing patterns of the network. This is because optimization embraced absolute distances as the only appraisal criterion, neglecting the role of directional change in determining the extent of spatial friction.
This latter problem informed the development of an alternative model, leading to the improvement of network optimization. Minimized detour path systems represented the refined product of what could be considered at all effects the resolution of a conflict between two criteria: in this case, absolute distance on one side and average detour factor on the other[80]. As such, they represent the ultimate stage of analog computing with respect to the experience of the German institute. Direct path systems minimized the in-between distance of locational couples with Euclidean lines, dragging detour factors to zero at the expense of average spans. Minimal path systems solved the issue with average spans through the rational segmentation of networks, boosting the general connectivity, but widening detour magnitude at the same time. Hence, minimized detour path systems incarnated the synthesis of the previous categories, prizing the balance between two ideally incompatible dimensions.
Eda Schaur (1991), Otto's partner at the *Institute for Lightweight*, overcame the hitches of soap film applications by means of an alternate model, based on the squeezing property of wool threads. Schaur's *wool thread model* included three main elements: a set of needles defining the points to be connected, a ball of yarn as raw material for connections, and a support device made up of glass plate and water tank. After fixing needles over the plate, the method consisted in unrolling the ball to derive one filament per each couple of needles. The arrangement of threads relaxed a direct path system with an extra-length, which calibrated the maximum allowed deviation for optimal outcomes. This has been a crucial passage with respect to input terms: in fact, the process took into account a quota of marginal length per thread as an additional constraint, informing the optimization of detour factors in *association* with total distance. After dipping the plate in the tank, Schaur detected the diffused compression of filaments due to the surface tension of water, which forced threads to muddle and shrink by keeping needles in the same position.
Schaur's wool thread model has been able to work out network solutions for a disseminated set of given points, optimizing the balance between total length of the system and average detour factor, which had been proposed at the beginning of the process. In view of a network able to minimize both metric and directional friction, the researcher used relaxation as a proxy for deviation ranges over theoretical direct routes. The result described a branching tree in which every point could be reached with a significant contraction of detour angles, dissolving all redundant patterns of connection (Schumacher, 2010).
Schaur's model shared the computational power of soap bubbles, despite relying on the simple contact between wool and water. With reference to this aspect, we should recognize the ability of both *analog* models to compute network solutions automatically, thanks to self-organizational instructions borrowed from chemical principles, within an interesting perspective of craftiness, economy and frugality. However, unlike what yielded by soap behavior, Schaur observed that the surface tension of pure water molded a distinct form at every iteration, depicting a spurious natural algorithm[81]. Someone may even interpret the absence of a unique optimal solution

[80] The sense of comparing two or more conflicting criteria is an aspect central to an intriguing and meaningful optimization perspective, especially when it comes to choosing an "efficient" layout within a field of complex equilibria like urban design.

[81] In fact, pure algorithms need to satisfy a fundamental principle of *uniqueness*: given a set of instructions, like plunging the threads in a tank, the output should be always the same at every iteration of the process. See section 1.2.2. for a detailed review of algorithmic properties.

as some sort of a “retaliation” measure for enhancing an already sophisticated model. Since we prefer less simplistic lines of reasoning, we rather appreciate this limit as an upright consequence of higher levels of complexity, reached, in this case, with compound conditions of performance[82].

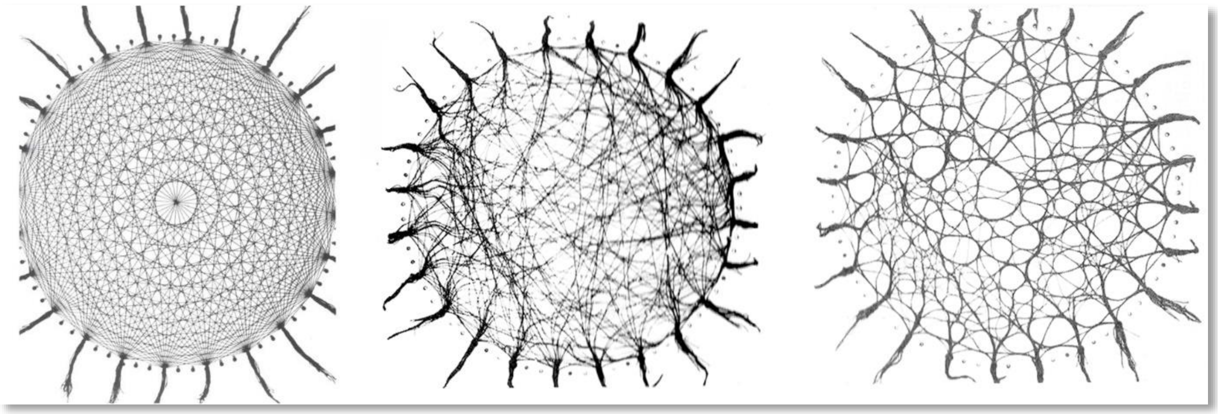


Fig. 58. Shaur’s *wool thread model*: from starting network (on the left) to optimized network (on the right) (retrieved from: https://it.pinterest.com/).

Otto’s *form-finding* models allowed for the analog calculation of architectural sweeps and urban grids through simultaneous and self-organizing force fields, which re-adjusted structural layouts at every change in occupation patterns. On one hand, these changes involved the configuration of linear boundaries for optimal surfaces; on the other, researchers could scroll both number and location of points by expecting the automatic reformulation of optimal path systems, where “optimal” denoted the structural performance of outcomes in supplying minimum energy networks.

Within this framework, any alteration of parametric profiles for every input information led to the automatic adaptation of emergent, self-organized forms, in line with not only a basic concept of *generativity*, but also the *autopoietic responsiveness* that is common to all parametric systems. However, the generative rise of optimality, despite boasting spontaneous origins, has also displayed its inertial “paleness” with respect to cumulative iterations: in fact, the exclusive endorsement of analog models implied huge costs for properly restoring preparatory conditions at every material computation, such as empting the tank for minimal path systems or procuring new wool threads for minimal detours.

In parallel, the *leitmotiv* of an architectural and planning technology learning from nature and its genius helped integrating parametric modeling with a sound purpose of structural quality, matching the idea of optimized performance with the replication of frugal energy patterns. Unsurprisingly, we can infer the relative success of these experiences noting that *Grasshopper*, one of the most recent (and powerful) *digital* tools for parametric modeling, includes components that are explicitly designed to simulate the same natural algorithms developed at the German institute since the 1960s, dumping the costs of analog material computation[83]. Something hinting how well the community of users understands the importance of Otto’s contribution to parametric design development.

[82] This actually mirrors what characterizes a *heuristic* optimization family, where the asymptotic nature of optimality calls for stopping at some point of the iteration process, due to the complexity of decision-making. See section 1.3.5.

[83] For instance, *Grasshopper*’s imitation of Otto’s computational experiences can be found in *Kangaroo*, a free plugin for minimal surfaces and path systems that emulates soap film algorithms (retrieved from: www.grasshopper3d.com/).

2.2. The digital extension of parametric design: predisposing the application to wider domains, based on gradual achievements in managing complexity

1.3.3. *Digital* parametric design: figuring performing solutions by means of artificial and customized systems of constraints, simulated through the use of virtual algorithms

Parametric design found in computing technology something more than a pure conversion of format. *Material computation* came upon several limits, which primarily concerned the freedom in defining constraint systems. From the earliest phase of development, *digital* parametrics qualified a major change in this respect, replacing "imposed" rules with "wanted" rules, shifting centrality from nature to humans.

Designers had no longer to submit their concept of "optimal form" to the generative essence of nature. Rather, they could reproduce (and *propagate*) their own generative essence. Along with the progressive sophistication of digital technology, this turn has reflected the gradual dispersion of practice from single, prominent authors to general trends of development. Following the avant-garde experience of architect Moretti, designers finally acquired the access key to diagrams, taking advantage from scripting as a way to formulate an ever-wider range of genetic principles. Setting up instructions by means of *virtual algorithms* sustained, in this sense, pure *generalization* and extreme abstraction of innate behavior, which has been crucial in preparing the ground for ever more complex forms. In truth, the first model of *digital computation*, developed by the American scientist Ivan Sutherland in 1963, could only operate *associative dynamics* across a bidimensional system of reference. Anyway, that has been just a prelude to previously unseen applications.

Properties of digital parametrics unlocked compound and multi-parametric definitions, supporting a concatenation of editable functions. However, generalization also unlocked the chance of constraining diagrams in terms of their procedural pattern. *Analog* and physical models directly internalized optimization because they embedded the intrinsic wisdom of natural systems, but, at the same time, it deprived designers of any room for targeting residual options. Instead, the digital counterpart enabled *fine-tuning* results so that they matched any other instance of the gradient while still complying with the same rule. In parallel, costly physical models of material computation could be dumped in favor of ever more popular and powerful computers. However, what truly concerns us is probably the empowerment of design domains getting close to the urban one. Particularly, this step relates to the ultimate and still ongoing phase of digital computation, which has triggered an increasing *specialization* of algorithmic models. A linear projection of this trend suggests that, in the future, planners and urban designers may benefit a lot from the expansion of what now is a "nebula" of single components and plugins explicitly dedicated to the performance of built environments. *Grasshopper* would most probably be at the core of this novel "control board" of parametric urban performance, given the interest of user communities and independent programmers. As recalled by the theorist Neil Leach (2009), this necessarily implies the joint protagonism of both designer and machine support, because the introduction of custom programming probes an unprecedented role of computers as integral parts of the design process itself.

> *«Not surprisingly in an age dominated by the computer, this interest in material computation has been matched by an interest in digital computation. Increasingly the performative turn that we have witnessed within architectural design culture is being explored through new digital techniques. These extend from the manipulation and use of form-generating programs that go beyond the use of the computer as a tool to understand, test out and evaluate already designed structures. [...] With this we see a development in the very nature of the architect from the demiurgic 'form-giver' to the architect as the controller of generative processes, where the final appearance is a product not of the architect's imagination alone, but of the generative capacities of computer programs»* (Leach, 2009, p. 35).

1.3.3.1. Ivan Sutherland: the pioneer development of CAD with the software *Sketchpad* and the figurative definition of "*atomic constraint*" in the 1960s

Analog form-finding came upon significant limitations, due to the exclusive reliance on natural algorithms. In this respect, the pioneer development of *digital* tools for parametric design, starting with the crucial contribution of Ivan Sutherland (b. 1938), helped expanding the array of morphogenetic rules with multiple constraint expressions, validating an "augmented" mimicry of *associative dynamics* by means of technological algorithms. Digitalizing computation has been a pivotal step toward calculations that were not feasible with *analog* devices: in much the same way Antoni Gaudí, Luigi Moretti and Frei Otto took advantage of existing laws of nature to calculate *select* parametric equations, Sutherland endorsed the use of computers as an opportunity to speed up the calculation of *any* parametric equation (Davis, 2013).

In his view, a system that enabled a "conversation" between man and computer would have been the key to a revolution for not merely design technology, but design thinking itself (Sutherland, 2003). Obviously, at a time when computer programming was still confined to an embryo phase of cold, *textual* editing, the concept of an interactive digital interface was a bold vision.

Working at MIT's *Lincoln Laboratory* for his doctoral thesis in engineering, Sutherland took advantage of the *TX-2*, a computer provided with cutting-edge power for its times, to develop *Sketchpad*, which he defined as a *man-machine* graphical communication system (Sutherland, 2003). Born in 1963, Sketchpad has been not only the first parametric modeling tool harnessing digital technology, but, more generally, the first interactive *Computer-Aided Design* program of architecture history (Tedeschi, 2014). Aside from its memory storage potential, the *TX-2* included three important elements: *1*) a *touchscreen monitor*, working jointly with *2*) a *light pen* and *3*) a *button box* as a complementary control board.

The idea of an interactive support system for design purposes, especially when it comes to conceive a monitor with touchscreen features, may appear commonplace today, but it was an absolute novelty for the 1960s. Contemporarily, the light pen allowed the researcher to draw directly on the monitor, incorporating a Graphical User Interface more than 20 years before the term was first used (Tedeschi, 2014), with utilities such as rubber-banding of lines, block managing, zooming and snapping. All characteristic operations we now see within CAD systems. As such, Sketchpad has been the father of modern interactive computer graphics, probably one of the most influential computer programs ever written.

The relational mechanism between light pen and monitor, the core feature designed for human-computer interaction, allowed designers to directly draw input geometric primitives, such as points, lines and arches: something common to what software tools like Rhino can do nowadays before importing objects into *Grasshopper*'s canvas (Tedeschi, 2014).

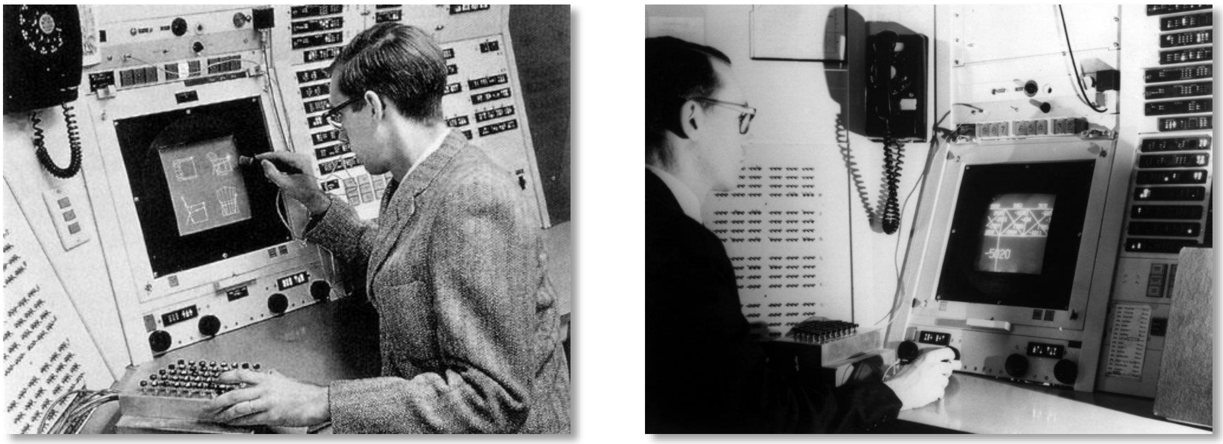


Fig. 59. Two photographs of Ivan Sutherland working with *Sketchpad*'s interface through light pen, touchscreen monitor and button box (retrieved from: http://www.computerhistory.org/).

Such primitives could then be related to one another according to an advanced *associative* rationality, represented by what Sutherland (2003, p. 17) called "*atomic constraints*": a set of fundamental expressions regulating the behavioral pattern of geometries through definite conditions. Sutherland's constraints could be considered as forerunning archetypes of *standard components*, since their role consisted in instructing the transformation of geometry. The *geometric operator*[84] was born in this context: through one particular *atomic constraint*, users could combine two similar primitives, such as two points localized in space, into a first level of assembly, such as their bridging line, which was governed by the union of all the constraints on its arguments, in this case the coordinate values. If two lines were drawn starting from the same point, every movement of that point implied change in both their magnitude and direction. Besides, these constraints could be combined to generate complex relationships among objects, overcoming the limits of additive drawing (Tedeschi, 2014). As another example, Sketchpad allowed constraining rubber-banded lines so that they always intersected at a precise angle. *Atomic constraints* represented *in toto* the operationalization of associative bonds, this time by means of digital algorithms built in a *virtual* environment, which debunked the expenses for practical construction that limited analog tests within *physical* reality.

For the first time, *Sketchpad*'s algorithms also provided the emulation of a *propagation-based* mechanism, since atomic constraints acted as a chain of simultaneous solvers (Woodbury, 2010). Although stuck into a bidimensional environment, the program boasted a quite advanced memory architecture to sustain propagation, which divided *master* drawings from *instance* drawings: the former were "ghost" molds shaped through atomic constraints, while the latter were memory-efficient copies of masters. Meant to rationalize the fabrication of serial models, these duplicates inherited the properties of master drawings, unless they were locally changed through the light pen tool. According to this master-instance dualism, based on dependency logics, changing the master drawing would have automatically propagated the same alterations through instance drawings, in any of their duplicates.

Fig. 60. A process of self-adjustment, starting from manual tracing by light pen, which provided input geometries, and heading automatically to a right-angled version, in conformity with the related constraint expression (retrieved from: http://www.madlab.cc/).

Unlike a precursor like Moretti, Sutherland never used the word "*parametric*" in his writings (Davis, 2013). In spite of this, we can credit atomic constraints with having all the essential properties of a parametric equation: in fact, each of them yielded an array of outcomes emerging from the elaboration of one or more independent parameters. The difference lied in the freedom of *programming* constraints: unlike with Gaudí and Otto's models, these parametric equations were not bound to the single physical laws of nature. In other words, they were not *mono-parametric*. They could actually compute *abstract* relationships, like parallel, orthogonal, and coincident, which gave forth to *user-defined* and *multi-parametric* perspectives of *form-finding*, meaning that they reproduced *custom* and *plural* morphogenetic rules.

That being the case, *Sketchpad* offered a new and stirring way to explore parametric modeling. Designers could explore the permutation of outcome geometry by modifying its basic parameters, expecting *Sketchpad* to automatically recalculate and redraw the geometry, not differently from what Gaudí, Moretti and Otto's models

[84] See section 1.2.3. for an insight upon algorithmic components.

could achieve by analog computing. However, digital computing unlocked the chance to edit not simply *variations*, but the *correlation* patterns of parametric inputs, i.e. the instructive content of algorithms. In *Sketchpad*:

> *«designers were also free to modify the relationships of the model, which would also cause the recalculation and redrawing of geometry. Thus the architect's control of Sketchpad, as with most parametric modelling software, is not only through the parameters of the model but also through the model's underlying relationships»* (Davis, 2013, p. X).

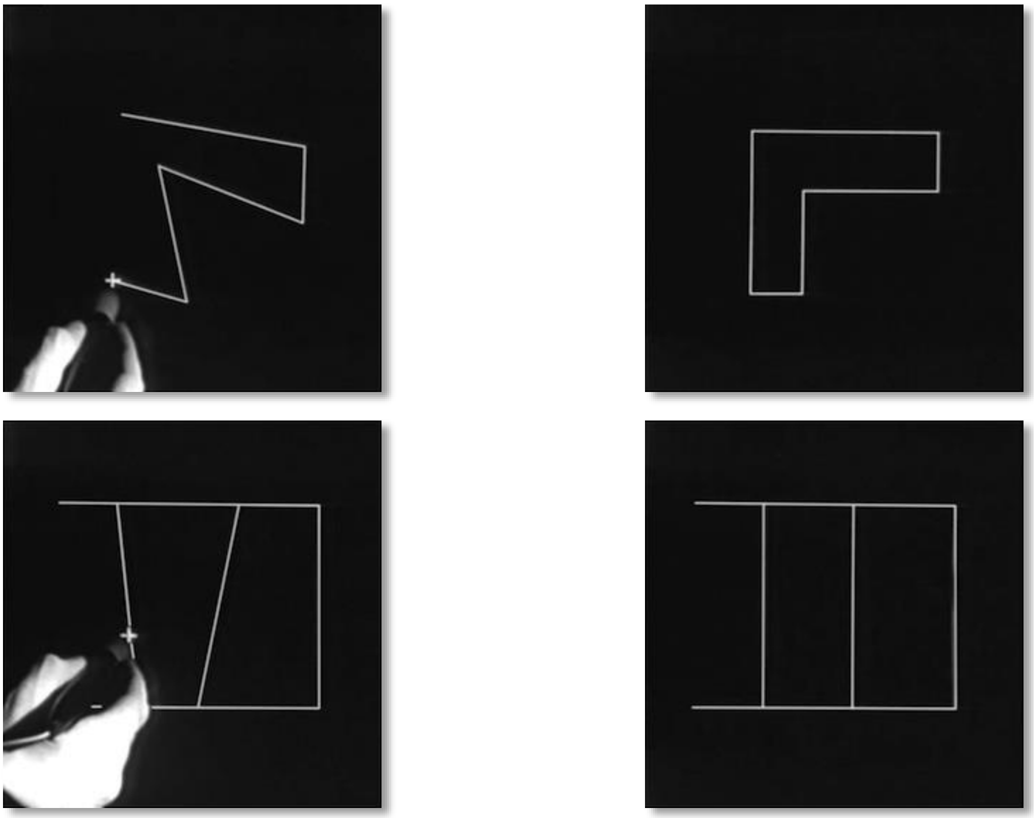
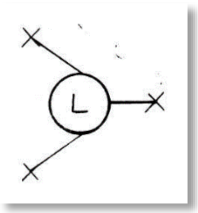
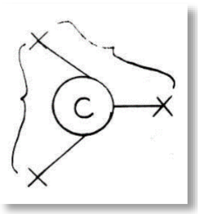
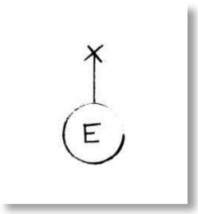
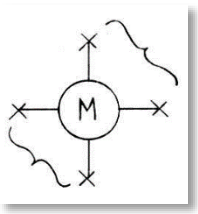
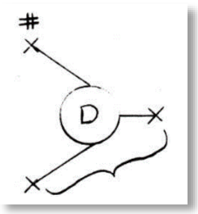
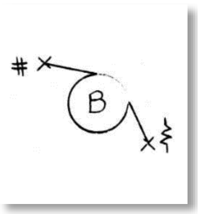
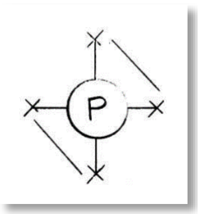


Fig. 61. Other examples of automated *responsiveness*, following the one in *fig.* X: according to a right-angle condition for intersecting lines, the software automatically "corrected" hand-drawn geometry with a predefined interpolation tolerance (retrieved from: http://lab.softwarestudies.com/).

Quite surprisingly, Sutherland anticipated the *visual* definition of algorithmic rulesets, a key achievement that we normally match with the newest developments of parametric design technology. *Sketchpad* helped the construction of drawing processes through a codified representation of constraints well before the advent of *visual scripting* languages, such as the one implemented in *Grasshopper*. Every atomic constraint could be recalled by typing its own identity code with the button box, as shown by the selection below (Sutherland, 2003, p. 117).

Representation	Code	Description and notes
	33L	**Fig. 62.** The definition of collinearity among three objects. No distinction about the order of input objects. Such constraint was generated automatically with the creation of points on a line.
	22C	**Fig. 63.** The definition of an equal distance from first to second object and from first to third object. Generated automatically when points were created on circles, with "first" being the circle center.
	24E	**Fig. 64.** The definition of a specific orientation for an object or a part of it, working with the support of mathematical vectors. Within Sketchpad's 2D space, the orientation assigned to an object reflects the link in the atomic constraint: in this case, we have a North orientation.
	34M	**Fig. 65.** The definition of proportionality between the distances of two couples: for example, users could set the distance from first to second object as 1/3, 1/2, 1, 2, 3 times the distance from third to fourth object.
	23D	**Fig. 66.** The definition of a scalar value (#) assigned to the distance between two objects, calculated in inches.
	21B	**Fig. 67.** The definition of a scalar value (#) assigned to the size of one particular object, calculated in inches.
	37P	**Fig. 68.** The definition of either parallel or perpendicular property for a couple of lines, one from first to second point and the other from third to fourth point.

After tracing basic primitives through the light pen, designers could make steps towards greater complexity by means of applying selected atomic constraints, chosen in accordance to a *procedural* sense. The final design was nothing more than the shape emerging from an ordered and meaningful concatenation of such constraints, interpreting the output of previous operations as an input for the following ones. Of course, this complied with the concept of parametric diagrams as *directed graph* structures, but it also served as an important inspiration

for *visual scripting* as we know it today. Within this framework, Sutherland embraced the *flow chart* as the clear depiction of a "*tree*" of dependencies between input data and design outcomes. *Sketchpad*'s flow charts were at all effects the (algorithmic) design of a process, and an interactive one of that too: visualizing data flows meant stressing their manipulation, with instant effects on the final drawing (Tedeschi, 2014).
This latter aspect enabled new opportunities grounded in the *autopoietic* behavior of *Sketchpad* models, despite the limitation to a bidimensional system of reference. However, activating the "control board" of morphogenetic rulesets brought about parallel criticalities linked to the inevitable increase of modeling complexity. Managing the underlying relationships of a parametric model[85] disclosed a sharper need for responsibility in selecting the "right" operations for the "right" purposes at the "right" moment (Davis, 2013). Architecture and planning projects are extremely sensitive to the content of these decisions and, sadly, do not deliver any "right" nor "evergreen" protocol to perform the choice.
Following the consideration of computational developments by Moretti in the 1940s, Ivan Sutherland's interface marked the beginning of a revolution in design technique. Nowadays, we can appreciate this breakthrough work of the 1960s in terms of both hardware and software contribution to parametric systems for modeling.

1. As a hardware support, the *TX-2* has been a genuine proof of how computers could automate repetitive drafting tasks with accuracy levels beyond compare, if we consider having manual drawing as the only alternative method.
2. As a software platform, *Sketchpad* proved that digital algorithms could be used not just for repetitive drafting, but also for an interactive *human-machine* interface, prospecting the support to creative tasks with parameters and, for the first time, constraint expressions as key elements of both concept creation and innovation (Tedeschi, 2014).

Interestingly, the first Computer-Aided Design system was parametric. However, the innovations brought by early CAD programs like *Sketchpad*, despite their significance, have been ignored even by successful commercial software like AutoCAD (1982), postponing the evolution of *associative* features until the 1990s (Tedeschi, 2014). Rather, AutoCAD enabled designers to speed up repetitive tasks and manage multiple layers, contributing more to the digitization of conventional drawing boards than to more substantial reformulations of the design process.

1.3.3.2. Samuel Geisberg: the development of the software *Pro/ENGINEER* in the 1980s, with an extension of components tailored to mechanical engineering domains

Digital parametric design has been furtherly developed in the 1980s, a booming period for personal computers, through the contribution of Samuel Geisberg, former professor of mathematics. In 1985, Geisberg founded the *Parametric Technology Corporation*, a Boston research institute, which gave birth to the first successful parametric software in commercial terms, called *Pro/ENGINEER*, in 1987 (Davis, 2013). The software represented a step forward in the automation of shape, even though intended for mechanical system design only (Tedeschi, 2014).
Similar to *Sketchpad*, the program allowed controlling both input and constraint expressions to associate parametric components. For instance, it was possible to create a link between a rivet and the relative hole. Besides, the change in rivet input size implied a *propagation effect*, which updated the model as well as its printing view (Tedeschi, 2014). But the main innovation with respect to Sketchpad, other than a wider set of constraint systems, consisted in the three-dimensional extension of geometry, which denoted the chance of exploring forms with greater realism catching up with a dynamic virtualization of physical models.

[85] In other words, *customizing* latent algorithmic structures with *user-defined* sequences of operations.

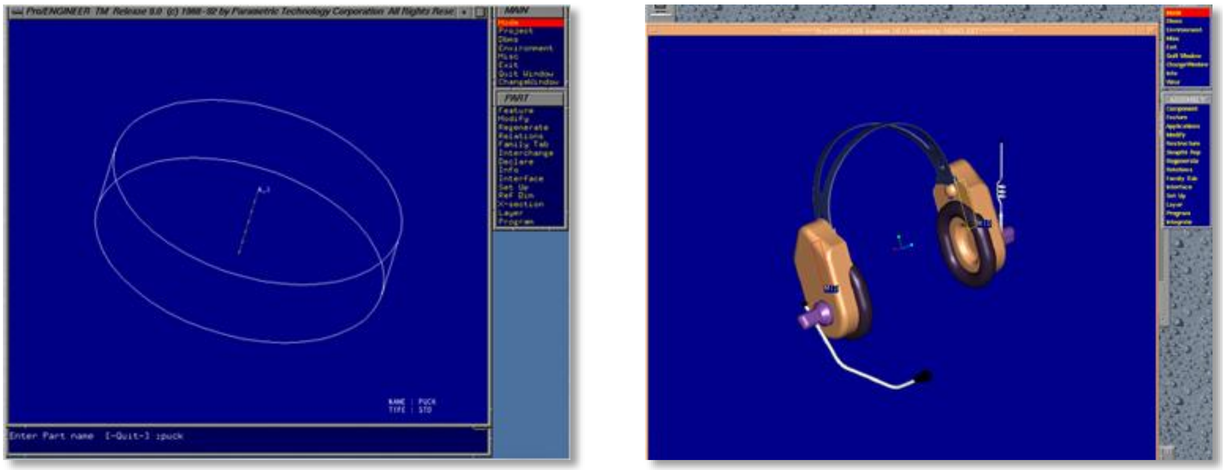


Fig. 69. A couple of screenshots showing the possibility to model associative geometries within the 1988 version of the software, breaking through the third dimension (retrieved from: http://www.digitaleng.news/).

Davis (2013) argues that Geisberg, expressing the original inspirations of *Pro/ENGINEER* during an interview in 1993, captured the broad motivation of parametric modeling as a general methodology for design synthesis:

> *«The goal is to create a system that would be flexible enough to encourage the engineer to easily consider a variety of designs. And the cost of making design changes ought to be as close to zero as possible. In addition, the traditional CAD/CAM software of the time unrealistically restricted low-cost changes to only the very front end of the design-engineering process»* (Geisberg, quoted in Davis, 2013, p. 31).

With his response, Geisberg pointed out two key purposes of digital parametric design. First, parametric modelling should be an enabling tool for designers who seek to explore a variety of designs. Although pledged to a very restricted disciplinary domain, Pro/ENGINEER proved to be valuable through the active manipulation of both input data and associative constraints.

Despite being explicitly tailored to mechanical modeling, the second point introduced a stronger thoughtfulness about the costs of changing models during dynamic design processes, where deferred decisions challenge parametric settings and formulae that initially seem to be appropriate to solve a problem. In this respect, Geisberg's *Pro/ENGINEER* cut down the cost of making design changes, inspiring a significant perspective of development for the success of digital tools.

The pervasive diffusion of computing technology, which happened mainly during the 1980s, fostered the implementation of a wide variety of novel techniques for architectural design and urban analysis, disclosing prospects that no one, probably not even Sutherland, could ever imagine for the following decades. The 1960s and 1970s had prepared an optimistic *humus* for computational models, spawning a variety of achievements compared to which Sutherland's vision of computers as augmenters for drafting seemed almost pessimistic[86] (Davis, 2013).

Despite the promising sophistication of such models, the innovations failed to penetrate architectural practice over several decades. At first, the failure was due to purchase and management costs of early commercial systems for electronic drafting, which required expenditure to the tune of some US million dollars per seat by the times of *Sketchpad* (Weisberg, 2008). A cost bearable by automotive or aeronautical companies, probably the most strategic and powerful ones, but rather prohibitive from the viewpoint of independent and associate architects and planners.

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[86] We can recall, in this sense, few computational methods going well beyond *Sketchpad*'s scope: design aided by evolution, with projects from 1966 (Frazer, 1995), self-replicating geometry and *CA* – cellular automata (Neumann, 1951), and shape grammars (Stiny, 1980).

Twenty years later, when computers started to become more and more affordable, AutoCAD seemed to have met the whole scope of computer-aided design; sadly, the software ignored the in-built intelligence of its CAD ancestors: a (preventable) lack of technology transfer and foresight that has certainly compromised the spread of parametric modeling across design fields of knowledge.
With its 2010 version, AutoCAD introduced parametric functionalities for the first time, forty-three years after *Sketchpad* was released. Despite the huge timeframe, the company sold the new feature with a seemingly sharp enthusiasm, as if it was a groundbreaking new capability: in absence of strategic awareness, it takes a while to realize the impact that revolutionary concepts like parametric design would have on practice (Davis, 2013).

1.3.3.3. Tailoring the tools for architecture domains: the inoculation of custom algorithmic programming and the isolation of input parametric options

Despite the absence of a central figure of reference, the period spanning from the late 1980s to the 2000s has shown a quite remarkable progress in the way digital tools proposed to manage design complexity, particularly with respect to a creative domain like architecture rather than mechanical systems. Within this framework, we can highlight two parallel, but seemingly contrasting achievements, both images of increasing complexity: on the one hand, Tedeschi (2014) acknowledges the expansion of programming practice at the level of constraints themselves, meaning that users, at least the most skillful ones, started to opt for an extensive customization of in-built functionalities. On the other hand, Davis (2013) recognizes the attempt at simplifying the assemblage of models by means of separating the manipulation of parameters from their processing mechanisms, so that parametric modeling could embrace architects alien to programming morphology. Both trends manifested the will to tailor parametric modeling to architecture, but with two diverging strategies.

According to Tedeschi (2014), a part of academic research has been trying to escape the simple editing boundaries of software, probing new ways to manipulate the application "from the inside" by means of *programming languages*, with an aim at enlarging the range of possible design solutions. This opened a way to finally access the "black box" of the program itself: shapes were generated through a custom combination of rules, but these rules, in turn, belonged to a pre-packaged stock of constraint expressions. *Sketchpad*'s *atomic constraints* were a clear example of this: designers could assemble their own tree of dependencies by choosing every constraint in full autonomy, but, at the same time, such constraints were bound to a predefined toolbox, limited to what Sutherland had chosen to develop while programming the software[87].
This "extreme" customization measure moved from the recognition that a selective sophistication of parametric programs could enable a management of complexity stretching beyond the boundary of software capabilities, structuring *ad-hoc* routines, i.e. routines tailored to the architectural scope of digital modeling. Of course, this modeling paradigm relied on a detailed knowledge of programming languages, which have always been cut out from architectural curricula. However, designers mastering such codes could inoculate custom instructions for the first time, leading to the integration of parametric algorithms with novel components (Woodbury, 2010).
As we can observe through several research projects conducted in recent years (Beirão et al., 2011; Duarte, et al., 2012; Koltsova et al., 2012; Schneider et al., 2011), the practice of customizing components by eviscerating parametric software marked a trend that does not seem to suffer any downturn. Aside from highbrow research environments, we can also notice a parallel development of add-ons, or plugins, shared through the incremental development of an Internet-based community of willing users, a "ritual" that is still going on. These plugins vary according to the parametric software of reference and consist in simple extensions of a parametric menu.

[87] In other words, predefined lists of constraints, like the one developed by Sutherland for *Sketchpad*, encountered a systematic limit in their own level of exhaustiveness, to be appraised in relation to the tasks emerging during architecture-specific modeling sessions.

Some of their components automatize a chain of already present components, in order to smooth the algorithmic process for architects that are mainly interested in *form-finding* explorations; some others introduce new instrumental contents[88].

Before introducing the "isolationist" trend, which has split the management of input data from their processing diagram, we first need to introduce the stream of tools following *Pro/ENGINEER*. Geisberg's software has been a relevant starting point. In 1993, the French company Dassault Systèmes incorporated many of its successful parametric features into *CATIA v4* (Weisberg, 2008). This software has been central to world-famous projects thanks to the close link with Gehry Partners. At that time, Gehry was employing a *CATIA* expert coming from the aerospace industry with a strong CAD curriculum, Rick Smith[89] (Davis, 2013). Smith has been a key technician for Gehry, as he helped realizing architectural projects that we still remind for their vanguard challenge to geometry principles. We can recall, for instance, the *Barcelona Fish* (1991), the famous *Guggenheim Museum* in Bilbao[90] (1993-97) and the *Walt Disney Concert Hall* in Los Angeles (1991-2003).

Fig. 70. A photo of the *Barcelona Fish* by Gehry, 1991 (retrieved from: http://profit.bg/).

Fig. 71. Photo of Bilbao's *Guggenheim Museum* by Gehry, 1993-1997 (retrieved from: http://www.bidc.eus/).

The worldwide success of these works led to the foundation of *Gehry Technology* in 2001, a sister company of Gehry Partners, whose scope was developing, refining and testing novel parametric modeling software. *Digital Project* was born within this context, in 2004 (Davis, 2013). The tool was not simply a direct successor of *CATIA v5*, for it embodied much of *CATIA v5*'s parametric engine with a further specialization of components, tailoring the toolbar for architects that, in Gehry's view, would have tried to rationalize geometry as characteristically complex as his own projects. Just as *Pro/ENGINEER* had been doing with its disciplinary "crew", *Digital Project* enabled architects to revise both parameters and operational chains, with a stronger accent on implements that would have replicated a fashionable, "willowy" style for contemporary architecture[91].

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[88] Over the recent years, particular interest has been dedicated to dimensions of performance related to energy modeling, spurring from an inspiration to responsible design criteria.

[89] Working as an engineer qualified for digital modeling, Smith has later become one of the most relevant critics of parametric design: the first one to admit a series of drawbacks with frankness, sanctioning the "sacred aura" that had biased the thought of his research fellows (Davis, 2013).

[90] One of the most iconic figures of world architecture, Gehry's *Guggenheim* has been considered as a catalyst of the so-called "*Bilbao effect*" (Ponzini, 2010), a powerful, yet deceitful narrative that has long been connecting Bilbao's renaissance to the spectacular side of the sole architectural piece, instead of considering how wider planning backbones had supported the overall renovation process.

[91] A curvy style that, other than being a *form-finding* consequence, reflected the burly use of *continuous* variables, moving along the algorithmic grid instead of being stuck into "*discreet*" alterations.

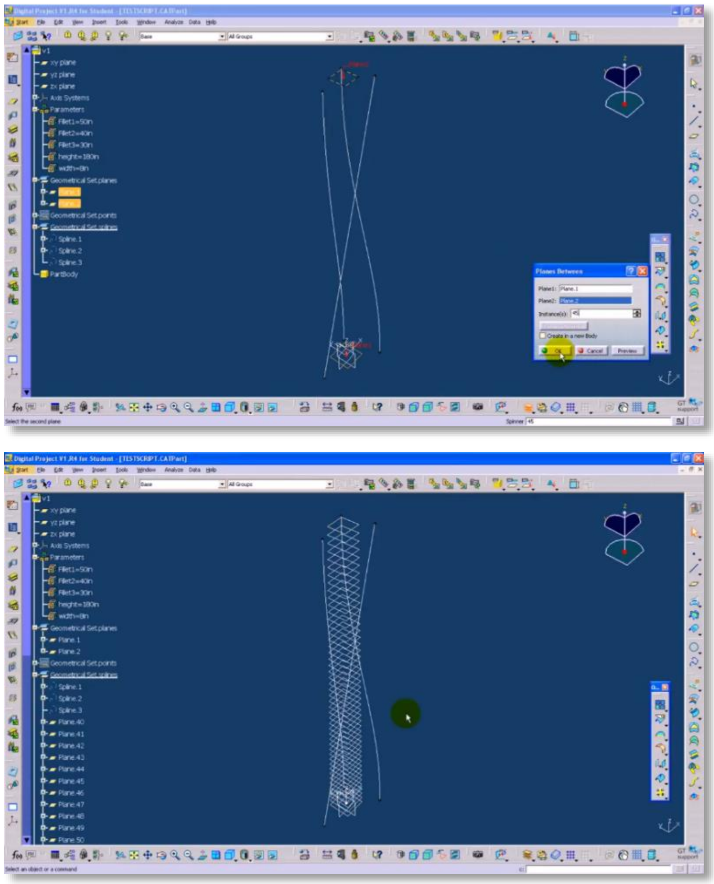


Fig. 72. Two screenshots showing *Digital Project* before (at the top) and after (at the bottom) a parametric modification of intermediate floors within a tower. Users could edit a text-based chain of dependencies through *ad-hoc* components for architecture, accessing a context editor when in need of input changes (retrieved from: https://www.youtube.com/).

By the early 2000s, architectural curricula had already vowed to digital design skills, with computers replacing the classic drawing boards. However, most architects were using workstations as unpretentious electronic converters of *additive dynamics*, sticking to devices like AutoCAD and its various competitors for elementary purposes, such as drafting with better precision and coordinating design layers. But the feeling of a more substantial revolution for design making pushed others to embrace specialist building modeling software, such as *ArchiCAD* and *Revit* (Davis, 2013).

Revit can be considered as exemplary of a different specialization strategy, consisting in the strict separation of parametric sliders from algorithmic convertors. *Revit Technology Corporation* (*RTC*) has been founded by former *Parametric Technology Corporation* developers, who sought to create the

> *«first parametric building modeler for architects and building design professionals»* (RTC, 2000, quoted in Davis, 2013, p. 25).

Revit epitomized the reliance on parametric equations at all effects: designers could regulate objects according to particular circumstances, based on an evident *associative* logic. However, we find a big difference within the organization of its human-machine membrane. In fact, unlike “explicit” modeling systems such as *Pro/ENGINEER*, *CATIA*, or even *Sketchpad*, *Revit* only displayed a library of predefined sliders, designed for architecture tasks, *hiding* their parametric relationships behind the interface. *Revit* and its kind were undoubtedly grounded in the use of processing algorithms; however, their focus emphasized the simple act of *using* parametric models, instead of *creating* them (Davis, 2013). For example, designers could change the pitch of a roof through sliding in-built parameters, observing the instant *revit* (or review) of all plans, elevations, sections, scheduled, dimensions, without any clue of the underlying diagram.

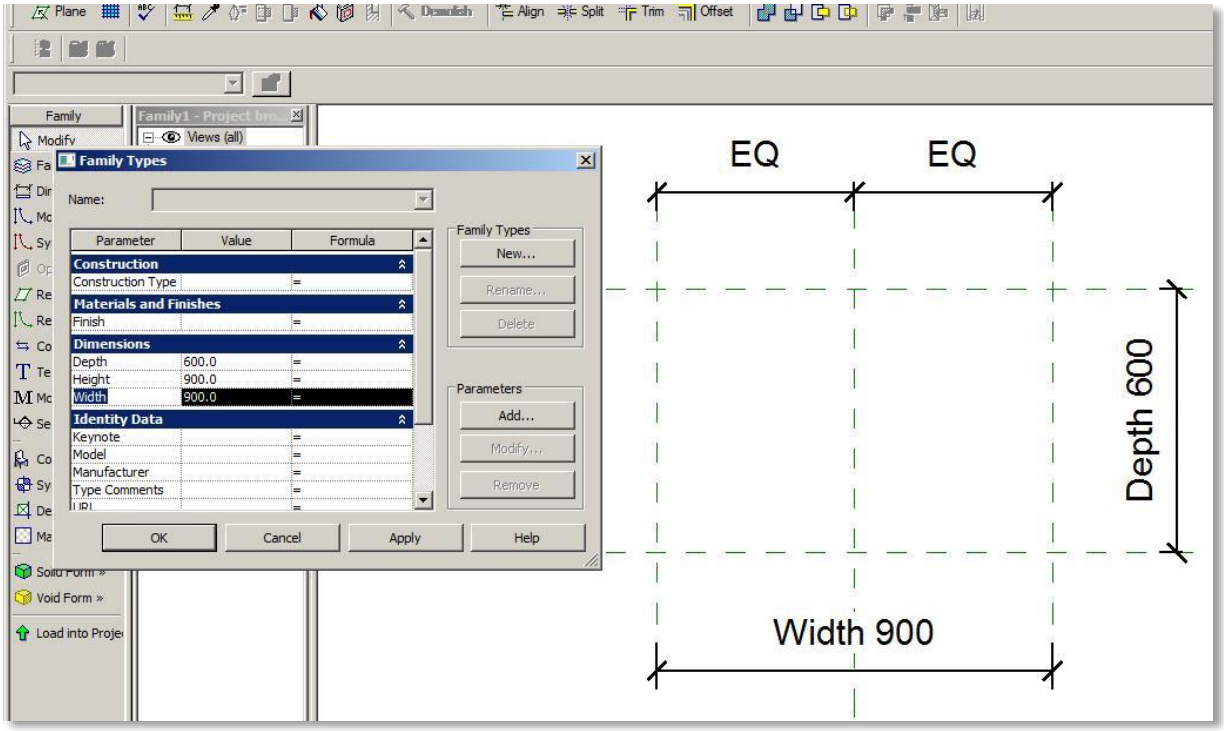


Fig. 73. A screenshot showing *Revit*'s implicit interface from the early 2000s, with a simplified controller of parameters on the left and a real-time viewer on the right. Based on a three-dimensional system of reference, the software proposed designers to directly handle a family of inputs across an embedded index of architectural features, manipulating either or both arguments and propagation order within a textual frame (retrieved from: https://www.youtube.com/).

In all likelihood, the acquisition by Autodesk in 2002 led to the assimilation of parametric features within the 2010 version of AutoCAD. Other than that, the company nurtured an ample rhetoric around this "light" and intuitive parameterization for architects (Weisberg, 2008). In parallel with an increasing customization of components, the distinction of such simplified interfaces from "pure" parametric modeling is still in progress. Both tendencies, despite deceptively in contrast with each other, emerged with a clear aim to *architectural* specialization for (digital) parametric design.

While customization still claims a *user-defined* toolbox in its effort to tailor parametric systems for architectural tasks, the isolation of inputs emphasizes the management of information, namely the parameters, as opposed to the management of the parametric model itself (Davis, 2013). In this case, architecture firms and professionals, despite the use of such modeling panels, may never consider they actually utilize parametric equations to some extent. Rather, they expect the release of ever more apposite functionalities from their reference vendor. However, who relies on custom plugins shares the same limit to another extent: designers with no skills in programming codes expect, in turn, the release of suitable sets of components from web communities, with little or no warranty about how well downloaded features stick to what they actually need[92].

[92] This is common even to the platforms providing plugins for *Grasshopper*, where a central principle calls for accepting every application "*as is*", that is, being aware that programmers are not responsible for potential crashes (retrieved from: http://www.food4rhino.com/).

1.3.3.4. The improvement of scripting interfaces as central parametric features: from *textual* to *visual* programming language with *Generative Components* and *Grasshopper*

The latest achievements of digital parametric design mainly concern the friendliness of interfaces without necessarily dumping the algorithmic background of software. Obviously, parametric designers have always found the key to human-machine interaction within scripting windows, owing part of their success to how well they communicated with computer systems. The automation of design tasks, which developed independently from associative modeling, has been a primary focus even back in the early 1980s, during the outburst of machines: the first version of AutoCAD, released in 1982, comprised an optional interface for writing code (Davis, 2013). Such measure granted Autodesk developers the occasion to

> *«avoid lots of custom coding and application-specific stuff [they would] otherwise get asked for»* (Walker, 1994, p. 115).

We can recall an example of custom coding with reference to the work of Mark Burry (2011), an architect now in charge of supervising the Sagrada Família. In 1992, ten years after AutoCAD's first release, Burry decided to try out its scripting window, in the attempt at modeling parametric hyperbolas for Gaudí's masterpiece instead of asking Autodesk to include a hyperbola function within a newer AutoCAD version: by means of programming, he developed his own, writing in *AutoLISP* code. His custom script, with its input parameters, processing instructions and outputs, represented the authentic reproduction of a parametric algorithm[93].
Following his application to hyperbolas, Burry confirmed his motivations for scripting in design, arguing the increase in productivity, due to faster iterations, and the gain in personal control, which allowed him to liberate himself from the limitations of "black-box" modeling software (Burry, 2011). As also claimed by Dino (2012), parametric designs find in the practice of scripting a consistent part of their foundational aspects:

> *«parametric systems are principally based on algorithmic principles [since] an algorithm takes one value or a set of values as input, executes a series of computational steps that transform the input, and finally produces one value or a set of values as output»* (Dino, 2012, p. 210).

Therefore, scripting interfaces are innately predisposed to the narration of parametric diagrams, because each parametric diagram reproduces a "script" for morphology to be played, within a specific dress, upon the "urban stage".
Though a figurative definition of algorithmic diagrams had already taken place in the 1960s, thanks to Sutherland's work with *Sketchpad*, scripting interfaces have employed textual languages as the leading codes for programming engineering and architectural products. These have not developed significantly since the early days of AutoCAD (Davis, 2013). Nevertheless, the 2000s have seen the introduction of *visual scripting* interfaces for the first time since *atomic constraints* have seen the light. *Visual* programming involves representing morphogenetic processes not as text-based lists, but rather as illustrated data trees, sticking to a *graph-based* conceptual representation of formal relationships[94].
Architects owe the first visual scripting interface to a central figure of digital modeling, the American designer Robert Aish (Davis, 2013). Working as a researcher for Bentley Systems, Aish dedicated himself to beta testing a new parametric software, *Generative Components*, in 2003. For the first time, architects could manage scripts

[93] More specifically, Burry's script for the hyperbola had three input parameters, which fed through a series of mathematical operators to output the final form: an origin point, a minimum point and an asymptote point (Burry, 2011).
[94] An interpretation we have presented as a mandatory step toward "*parametric thinking*", as seen in section 1.1.4.3. Aside from *Sketchpad*'s algorithms, Davis (2013, p. 164) detects two notable precedents from the 1990s: *MAX/MSP*, which is popular with musicians, and *Sage*, later rebranded as *Houdini*, which is popular with visual effects artists.

by connecting selected components that displayed parameters and operators as graphic, "drag-and-drop" panels. Few years later, Robert McNeel & Associates, a company that had acquired popularity thanks to Rhinoceros, tried, unsuccessfully, to license *Generative Components*. As a response, the enterprise charged David Rutten[95] with developing its own parametric system (Tedeschi, 2010, p. 28). After a first release in 2007 as a plugin for Rhino 4.0 called *Explicit History*, Rutten dubbed the new interface *Grasshopper* in 2008.

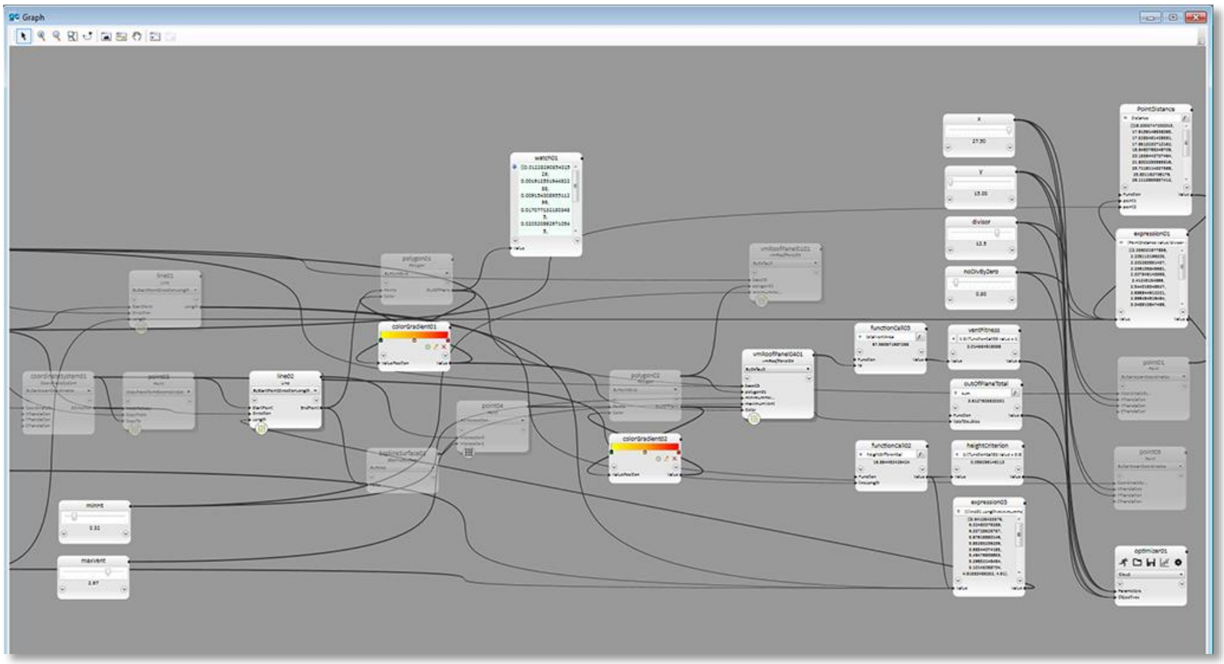


Fig. 74. A shot of *Generative Components*' *visual scripting* interface, Bentley Systems (retrieved from: http://blog.interfacevision.com/).

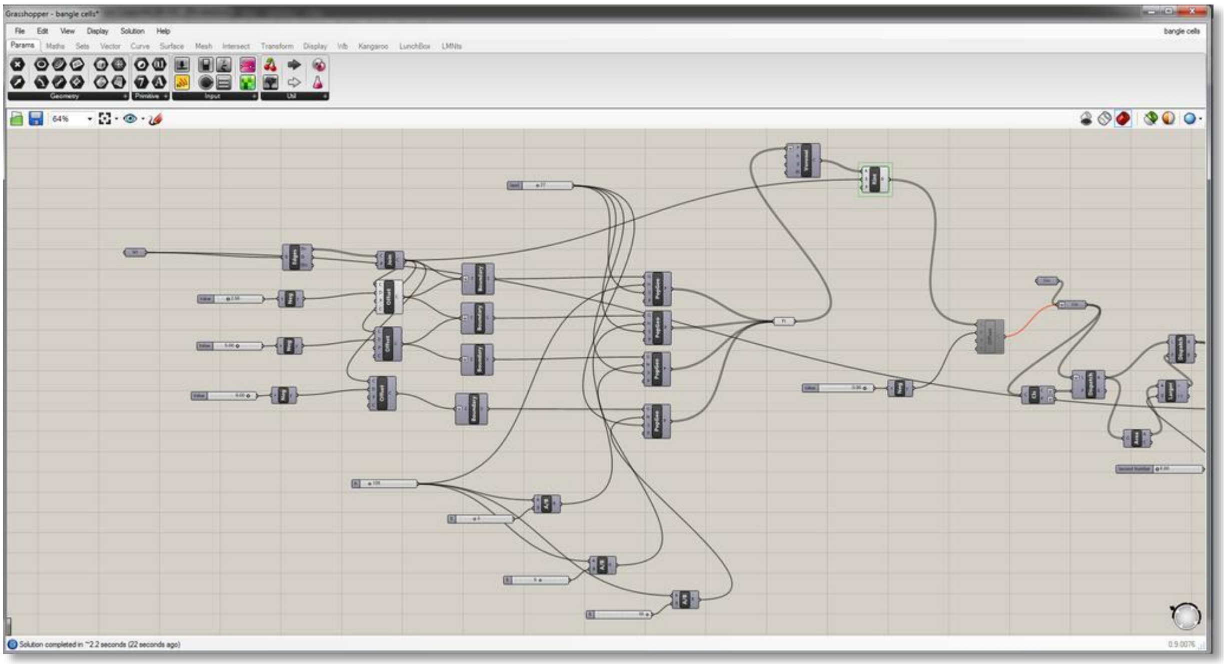


Fig. 75. A shot of *Grasshopper*'s *visual scripting* interface, Robert McNeel & Associates (retrieved from: http://i.imgur.com/).

[95] David Rutten is a graduate of TU Delft Architecture and Urbanism faculties. He has been working for Robert McNeel & Associates since 2006 on several programs, the most important of which is *Grasshopper*'s *visual programming* environment for Rhinoceros 3D (Tedeschi, 2014).

1.3.3.4. *Grasshopper*'s achievements in dealing with complex modeling: approaching the urban design dimension with a simultaneous combination of diverse data sources

Both *Generative Components* and *Grasshopper* are *node-based* editing platforms based around *graphs*, i.e. directed flowcharts that map the flow of relational dependencies from parameters to the generation of outcome geometry, passing through operators chosen directly by users (Davis, 2013; Tedeschi, 2014). Clearly, this means that both devices inherit the *autopoietic* property of all previous parametric systems: changes to parametric settings or to their processing patterns cause the alterations to propagate across the whole diagram, leading to the automatic update of geometry.
However, despite the availability of *Generative Components*, we should also appreciate the increasing appeal of *Grasshopper*'s interface and language as the chief software features of our times, as witnessed by both thinkers and practitioners of parametric design (Beirão et al., 2011; Rakha & Reinhart, 2012; Davidson, 2013).

> *«Grasshopper seems to be winning out in the competitive struggle for domination as the preferred tool for scripting, at least in the avant-garde segment of the discipline, both on the diagrammatic level as well as on the level of concrete modelling. The great advantage of Grasshopper is that it transposes most of the scripting syntax into graphic network language. The system of parametric dependencies that organizes the internal variability and differentiation of the model can now be configured and manipulated via a second order diagram that controls the first order diagram or model»* (Schumacher, 2010, p. 354).

Within a few years, *Grasshopper* has become one of the most popular and advanced parametric modeling tools, captivating a vast community of users and developers, including not only students and qualified scholars, but also independent professionals (Tedeschi, 2014). The idea of a "sharing community" gravitating around *Grasshopper* becomes of primary importance: in fact, reaching a critical mass of practitioners can play a big role in achieving self-powered systems of assistance, paving the way to ever more affiliates. These can test *Grasshopper* as a free download; however, the platform requires a licensed copy of Rhinoceros 5.0 or higher. Aside from its costs, the combination between Rhino and *Grasshopper* sets up an unrivaled *form-finding* platform, due to the benefits of several characteristics that go beyond the introduction of *visual scripting* by *Generative Components*.
In particular, Tedeschi (2014, p. 34) highlights five main achievements, compared to previous devices:

1. *A wide, dynamic and growing community* – *Grasshopper* does not end up with "solitary", remote modeling: it is, rather, at the center of a dynamic cyber-community, which connects several users who share works, knowledge, ask questions and discuss challenging problems, exchanging instructions, algorithmic solutions and examples from experts to beginners.
2. *A constant software updating cycle* – As a direct consequence of web-based interactions, *Grasshopper* can also boast constant updating cycles and improvements consisting in new packages of components and bug fixers, both based on the active feedback of users.
3. *An ecosystem of tools for an integrated workflow* – Independent programmers provide a wide series of additional plugins designed to integrate workflows with *ad-hoc* components. Such "plugin ecosystem" represents a huge multiplier for Grasshopper's parametric potentials. For instance, plugins can reproduce dynamic simulations, physics, structural and environmental analysis, based on the morphological qualities that spring from parametric settings.
4. *Software interoperability* – This is a huge quid plus for a dynamic workflow: when designing *Grasshopper*, Rutten considered the potential to interact with other software systems. Grasshopper's interoperability does not embrace simply compatibility-based interchanges of static files, but also dynamic, real-time transfers between algorithmic diagrams and external software, such as *Excel*, *Photoshop*, *Revit* or *Ecotect*.

5. *Hardware interaction* – Some of the plugins developed for *Grasshopper* are explicitly designed to enable interactions in both data input and output with hardware platforms different from Windows, such as Mac OS, Arduino and Kinect.

These software devices can be combined within a single workflow pattern including diverse, but complementary purposes, ranging from statistical analysis to graphic adjustments, passing through practices of ecological and energy testing. This latter feature, being of primary importance in relation to the "compositional problem" of urban development, will be our particular concern for exploring *form-finding* researches.

2.2.7. The impact on urban design perspectives – *Forward* and *inverse design* through the integration of diversified indicators: fine-tuning and generalized optimization of designs

Along with the parallel sophistication of computing power, the gradual absorption of manifold sources of data within a parametric system has opened a "chest" of opportunities for design to manipulate form not only dynamically, but also consciously. As wisely recalled by Beirão et al. (2012), the design models we are accustomed to, namely CAD systems, incubate shape as a completely separate process from both analysis and evaluation. Based on the various attainments of ultimate parametric platforms like *Grasshopper*, moving through a galaxy of simulation plugins by means of a single, but augmented algorithm may set up an integrated design workflow, with an in-built support to design decisions. Here, the idea of simultaneity clearly plays a big role, since it helps increasing the awareness of impacts that specific parametric settings may have on resulting performance.
The diffusion of custom components, which may allow for both importing context information and assessing design responses, has been enforcing the interactive alchemy between designers and parametric environments, bridging the practice of manipulating parameters with testing resulting designs against one or more goal indicators[96]. In particular, correlating a formal layout with a variety of context layers and indicators is a key passage for appreciating parametric systems as devices for imagining up-scaled urban design approaches, which draw value from multi-layered information to manage the complexity of contemporary cities (Batty, 2007). The perspective of urban design emphasizes the need for continuous analysis and evaluation cycles even more than architecture, due to the recognition of effects (and responsibilities) insisting on wider spectra at a larger scale (Portugali, 2011). Thus, overcoming the strict separation among the processes of analysis, synthesis and evaluation, while indulging their natural twist (Lawson, 2006), can frame parametric design and its amplified functionalities as a plausible support for improving both adaptive responsiveness and quality of design decisions (Ascher, 2001).
The expansion of virtual algorithms with an extra-layer of evaluative constraints, namely the indicators, reflects the chance for designers to permute a model[97] by means of two different behaviors, traveling along two different ways of instructing computational generativity. In fact, users can interactively control such model by either altering root parameters (*forward design*) or setting minimized, maximized or target values for output indicators (*inverse design*), provided with looped solvers of optimization tasks[98]. In other words, the intended results would require, on the one hand, careful parameter tuning and constant observation of output indicator values; on the other, the process would be utterly automatized, computing selected parameters "inversely" so that they match a specified indicator value.
This concept of indicators as direct outputs of formal change may act as a strong fertilizer for urban design and planning practice, as these measurement systems, other than being consolidate practice of composition (Fox,

[96] Of course, this trial-and-testing process wouldn't boast neither speed nor simultaneity without the support of *associative dynamics* among algorithmic components.
[97] In this case, an urban design one.
[98] E.g. *Galapagos* for *Grasshopper*.

2015; Murphy, 1980; Paolillo, 2010), do represent assessment criteria for monitoring, addressing and motivating design choices toward the increase of built environmental quality (Puerari, 2011). Of course, this role tends to acquire dramatic relevance especially when we deal with intensive transformation processes. Moreover, the direct link between input parameters and output indicators seems to support the evolution of design processes, as it structures cognition through "see-move-see" increments that have some influence in conferring a *reflective* attitude to design options (cf. Schön, 1983). This augmented consciousness may reflect the extent of effects as we "zoom out" and see the picture of an urban, more than a simply architectural environment.

The ongoing specialization of evaluative components confirms and steers the access to intuition in controlling design instances, while experiencing, at the same time, the assimilation of refined measures. User-defined constructions of algorithmic matrixes, which denote the major achievement of digital parametrics, allow for combining measures of geometric properties that may have straightforward connections with inputs from a cognitive point of view, such as the average distance of a house from the street or floor-to-area ratio[99]. The introduction of specialized simulation plugins, as a custom empowerment of algorithms, has been providing users with metrics of more complex semantic. Within this framework, we can appreciate components devoted to the calculation of landmark visibility (Koltsova et al., 2012; Koltsova et al., 2013), amount of sun exposure per building (Amado & Poggi, 2014), suitability of roofs for solar panels (Kanters & Horvat, 2012), water consumption (Krishnamurti et al., 2012) and walkability (Reinhart et al., 2013). All measures that do not perform an evident relationship with input parameters. Nevertheless, establishing *associative dynamics* between formal change and resulting performance through this "plugin ecosystem" (Tedeschi, 2014, p. 34) currently contributes to explicit and synchronized liaisons that would be otherwise unknown and highly non-linear (Vanegas et al., 2012). In this sense, synergizing refined indicators with parameters could enable a still intuitive, easier and faster evaluation of models, in spite of an increased level of depth and complexity.

The development of a "cloud" that supplies real-time interactions between parameters and plugins for various metrics may represent an occasion for settling the base of a "missing link" we have long been hoping for planning. As *associative* logics can correlate geometric models with data, parametrics may rank as meaningful systems (and consolidate practice) for assessing, confronting and motivating design decisions in the coming years of the information era (Gil & Duarte, 2008). Imagining the execution of these accomplishments is only possible through *digital computation*, with its chance to unlock a variety of (user-defined) grids toward (simple or compound) custom and specialized indicator sets, as opposed to the margins of *material computation* discussed in the previous chapter.

[99] Besides, these indicators can be assembled through simple mathematical components that we can find in toolbars, such as the four fundamental operations (addition, subtraction, multiplication, division) or descriptive statistics (for example, average and standard deviation).

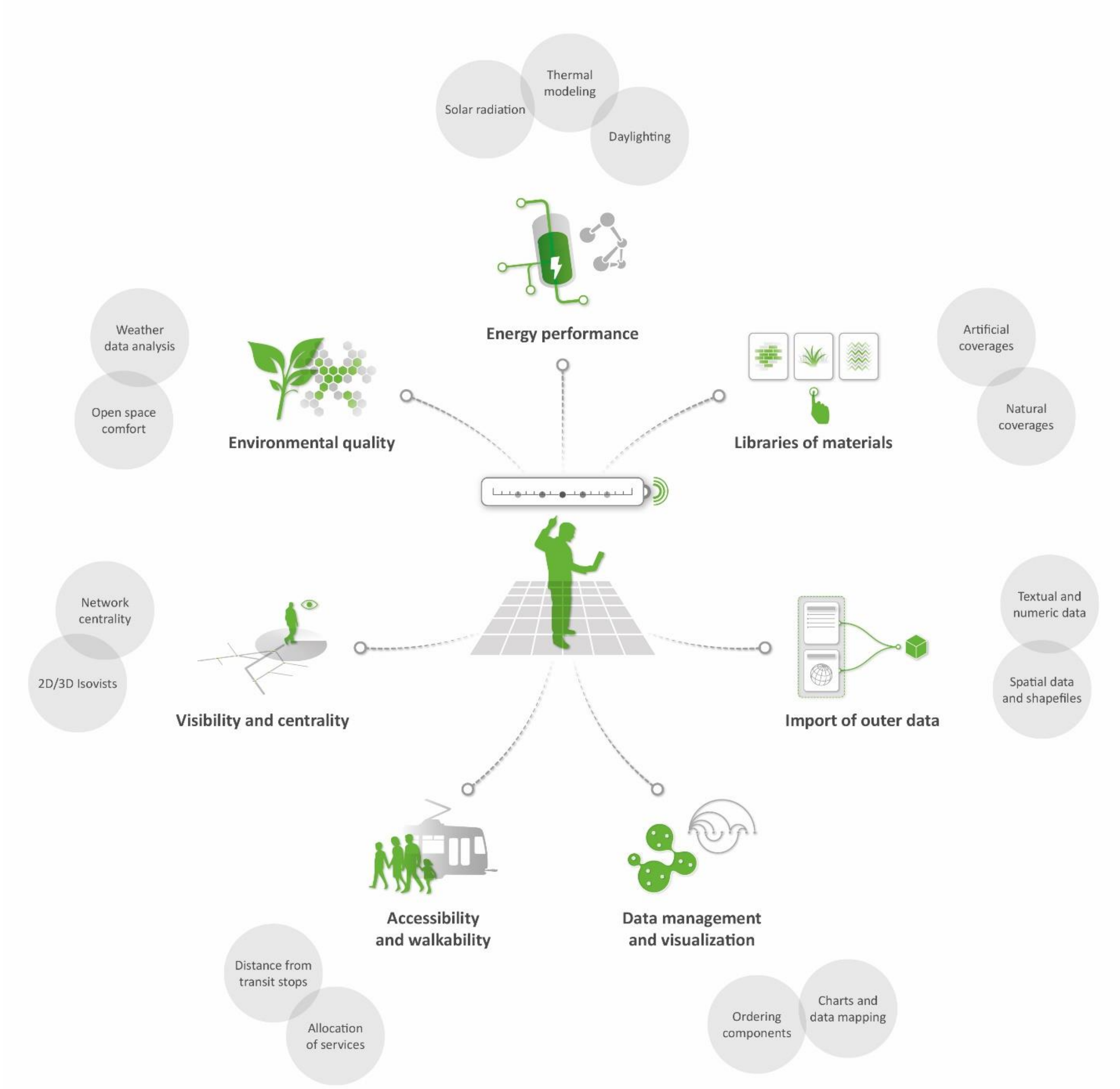


Fig. 76. Through an expanding "cloud" of specialized plugins, programmed for various dimensions of the urban realm, parametrics may serve more and more as a tool for exploring the multi-faceted impacts of urban compositional choices (source: author).

With reference to this "galaxy" of diagnostic supports to decision, we can find fundamental tools for expanding the scope of urban design implications, and complementary devices for governing, representing and informing analytical functionalities and their hunger for data. The magnet-like system of specialized components reflects the manifold manifestations of parametric change in its complex relationships with not only a set of substantial effects on space, but also the organizational aspects of information required to both connote and simulate such effects. Users can access a battery of custom components through online portals dedicated to sharing additional contents for parametric software. By recognition of *Grasshopper* as the most diffused and successful parametric tool of our times, designers pledged to urban analytics and evaluation processes typically resort to well-known and officially certified websites for downloading executable plugins. After sifting the extra-features available at the two leading portals for parametric contents[100], we can appreciate seven areas of development in strict contact with the alteration of complex shapes: energy performance, environmental quality, visibility and network centrality, accessibility and walkability, data management and visualization, import of outer data[101] and libraries of materials[102].

Specialized dimension	Examples of plugins	Descriptions and notes
Energy performance	*DIVA, ArchSim, Ladybug*	Daylighting and solar radiation analyses for different spans, electric lighting calculation and thermal zones.
Environmental quality	*Ladybug*	Analysis of weather data, wind distribution, shadow densities, psychrometric examination of open spaces.
Visibility and centrality	*Decoding Spaces*	Preparation of networks for centrality analyses and calculation of formal indexes such as *Closeness* and *Betweenness*.
Accessibility and walkability	*Smart Space Analyzer*	Calculation of walkscores and distances between given points, such as transport hubs, and every other point.
Data management and visualization	*Slingshot!, Mr.Comfy*	Visualizing and ordering data for effective diagnosis; simulation components can act as data sources.
Import of outer data	*Heron, Elk*	Import of GIS data from different sources, such as local and online shapefiles or OSM layers, with instant location and scaling.
Libraries of materials	Concrete, plastic, carbon fiber	Separate instance materials that can be collected in personal libraries, classifiable according to colors and physical properties.

Tab. 1. Examples of plugins that can be used for urban massing evaluation within *Grasshopper* environment (retrieved from http://www.grasshopper3d.com/; http://www.food4rhino.com/).

Outlining at least the main families of additional components that are under development for diagnosing spatial choices is of primary importance, not only in terms of potential shifts toward neighborhood scales, but also in relation to user-defined ways of conditioning performance through custom algorithms. In fact, unlike what happens with material computation, where nature represents "*the*" condition for optimal shapes according to restrained aspects, digital parametrics can frame the output values of selected and arbitrary indicators as targets of both fine-tuning and optimization practices. Perhaps, this is the most notable implication of artificial algorithms, as these now attain to upper levels of abstraction and generalization where forms comply with *optional*, rather than *forced* conditional undertones[103]. The *associative* self-consistency of parametric models plays a crucial role here, since it supplies the ceaseless re-amalgamation of outcomes against *our own* benchmark values,

[100] We refer here to *Grasshopper 3D – Algorithmic modeling for Rhino* (available at http://www.grasshopper3d.com/) and *Food4Rhino* (available at http://www.food4rhino.com/).

[101] Both GIS *shapefiles* and non-spatial information, such as *Excel* tables.

[102] The latter being useful extensions for both designing realistic renders and informing energy and environmental analyses, since each of them has sensitive properties like specific albedo and thermal conductivity values.

[103] We can see an example of this achievement with reference to Otto's minimal surface experience (2003). The use of soap bubbles as means of material computation helped reaching frugal standards, but conformed the generation of shapes to (*one*) mathematical definition, i.e. the amount of output area units. Within the digital realm, Otto and his colleagues at *IL*

even by keeping up with generative criteria that we cannot find in natural systems. For instance, despite being a natural driver of life on Earth, we cannot expect the Sun to shape and reshape solid substance toward maximal reception of illuminance. In the meantime, all would tend to dust, shattered by light. Hence, the incorporation of digital computing would serve as a practical means to emulate and accelerate such process in direct relation to design intents.

Aside from being a major trend of specialization within the "ecosystem" of plugins, the issue between compositional choices and solar opportunities pertains to a framework of targeted improvement and generalized optimization of morphology patterns. Given explicit input coordinates, energy-oriented plugins for *Grasshopper* such as *DIVA* or *Ladybug* represent the chance to internalize the simulation of solar impacts within algorithmic routines of assessment. This is something that automatizes pre-parametric experiments that had been carried out on building envelopes, where urban shapes emerged from invisible "boundaries" outlined, in turn, through casting the relative motion of the Sun (Knowles, 2003). Shifting from material to digital computation supports, these plugins can drive refined chiseling and carving processes by means of tracking Sun paths in artificial and sped up fashions, acting as unprecedented resources for architects and urban designers. In this sense, harnessing the potential of digital simulation and appreciating the *associative* relationships between solar performance and parametric prototypes may help designers predisposing form to adequate illuminance and radiation levels, suggesting strategies for arranging virtuous solutions to the compositional problem.

would have been able, rather, to privilege (and maybe combine) alternative optimization criteria. In other words, different output indicators could have been selected as *fitness* functions of a custom optimization process, adapting outcome surfaces to other (and maybe more complex) performance dimensions, like the ability to cushion whirlwinds or the maximization of solar capture in relation to the minimum possible area.

PART 3 CASE STUDIES AND MATTER FOR REFLECTION

Interpreting practical experiences as attempts to address the “*compositional problem*”: predisposing occupation of shapes and densities parametrically to solar energy gain

3.1. Case *A* – The energy simulation of generic urban models, starting from the manual combination of definite built forms, layout options and density arrangements

This first parametric experience interprets the twist of both horizontal and vertical informers as a matrix yielding different energy impacts along a scale of densities. Such grid makes explicit reference to the opportunity of exploring the room for compaction, longing for ways of combining geometries so that they stock as much floor area as possible while insisting on a limited (read *conflictual*) reference surface. In particular, the conflict stands in the importance of taking advantage from available land without defacing the access to energy benefits, which typically require an intelligent distribution of urban coverage and roughness through space.
Specific levels of 3D obstruction emerge from intersecting instructive norms related to both density and shape. In turn, both dimensions of shape and density specify horizontal and vertical patterns of occupation. The overall set of patterns conflate on the use of basic square resident units, informing either or both aggregation/rarefaction and low-rise/high-rise developments (Cheng et al, 2006). In terms of density, the research discriminates the parametric input of *site coverage* [%] as its horizontal manifestation, while *plot ratio* [m^3/m^2] represents its vertical impact. The options for site coverage inform an either *low* or *high* horizontal obstruction, 9% and 36% respectively; plot ratio, on the contrary, describes the entity of vertical obstruction with three levels: 1,4 for *low*, 3,6 for *medium* and 7,2 for *high*.

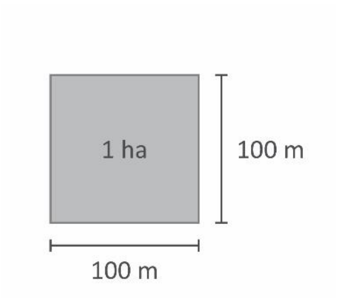


Fig. 77. Solar radiation map of the optimized scenario (source: author).

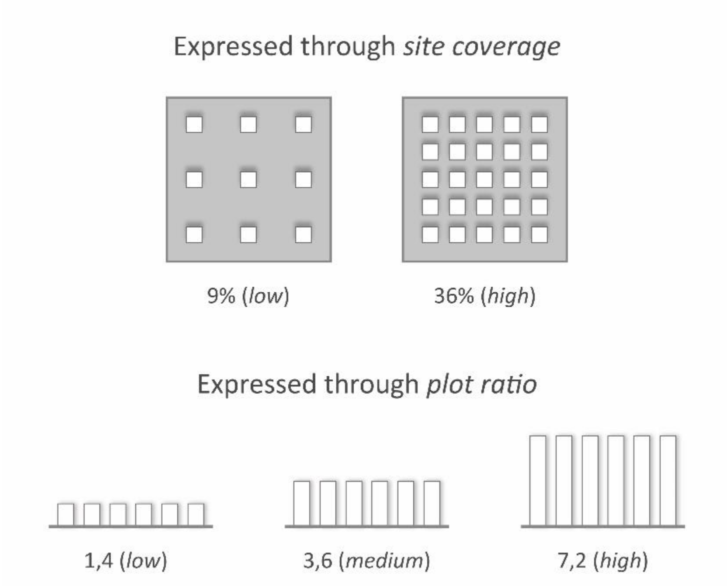


Fig. 78. The parametric options chosen for density configurations: site coverage for horizontal layout and plot ratio for vertical layout (source: author).

If site coverage and plot ratio play as multipliers of, respectively, horizontal and vertical obstruction, *randomness* represents the incident alteration of their distributive quality. Each manifestation of density intersects this lateral input across its binary option: we can have no randomness at all, meaning strictly stereometric regularity, or we can assign a *seed*[104] of random values to unleash the dispersion of either horizontal or vertical outlines. The series of seeds, one per each possible amount of horizontal and vertical occupation, originates from listing random numbers through a basic Excel function, while plain regularity, as a human construct, presupposes the indiscriminate evenness of patterns, solved through equal spacing along the two dimensions, and equal stretching along the third one.

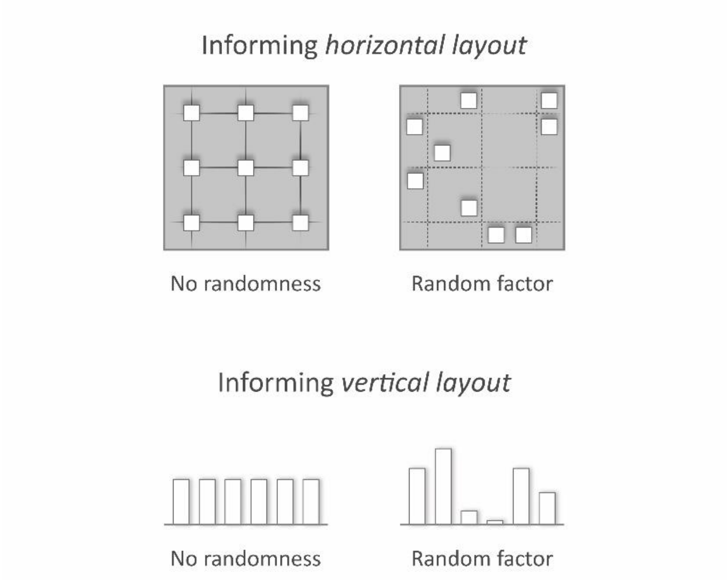


Fig. 79. The parametric options chosen for formal configurations, with the application of two degrees of randomness to horizontal and vertical layout: total uniformity and a random seed (elaboration from Cheng et al., 2006).

Through the mutual exclusion of parametric options per each of our three filters, the scholars conceive a battery of alternative scenarios, one per every interception of site coverage, plot ratio and either or both horizontal and vertical randomness. More specifically, the telescoping of such rules produces eighteen instances, summed up in the table below. Despite losing exhaustiveness with the bottom models, the matrix shows a significant effort to assort and combine preset conditions for emerging patterns.

[104] In other words, a field made up of records describing a unique sequence of numbers.

Case	Form (H, V)	Site coverage	Plot ratio	Floor area
1	Uniform, Uniform	9%	1,4	14.000
2		9%	3,6	36.000
3		9%	7,2	72.000
4		36%	1,4	14.000
5		36%	3,6	36.000
6		36%	7,2	72.000
7	Uniform, Random	9%	1,4	14.000
8		9%	3,6	36.000
9		9%	7,2	72.000
10		36%	1,4	14.000
11		36%	3,6	36.000
12		36%	7,2	72.000
13	Random, Uniform	9%	1,4	14.000
14		9%	3,6	36.000
15		9%	7,2	72.000
16	Random, Random	9%	1,4	14.000
17		9%	3,6	36.000
18		9%	7,2	72.000

Tab. 2. The 18 generic models emerging from the assorted intersection of input values/options (retrieved from Cheng et al., 2006).

In other words, the emerging arrays of standard units represent nothing more than the (*im*)balances conceivable between degrees of density, geometry of shapes and solid-void relationships, leading to various prospects (and effects) of occupation within the boundaries of a fixed domain. In this case, the scholars opt for a fictitious site shaped as a flat square of 1 hectare (100 x 100 meters). Having enough information to set up definite instances, the research consists in the manual reconstruction of maquettes through *Digital Elevation Modeling* sessions, one per each of the eighteen cases above. This means that the approach, while considering the permutation of input setting as an *abstract* determinant of several *concrete* forms, describes the plain substitution of machine-led *association* logics by human-led *addition*, which will lead to recognize digital algorithms as essential tools for augmenting the investigation of morpho-energetic performance.

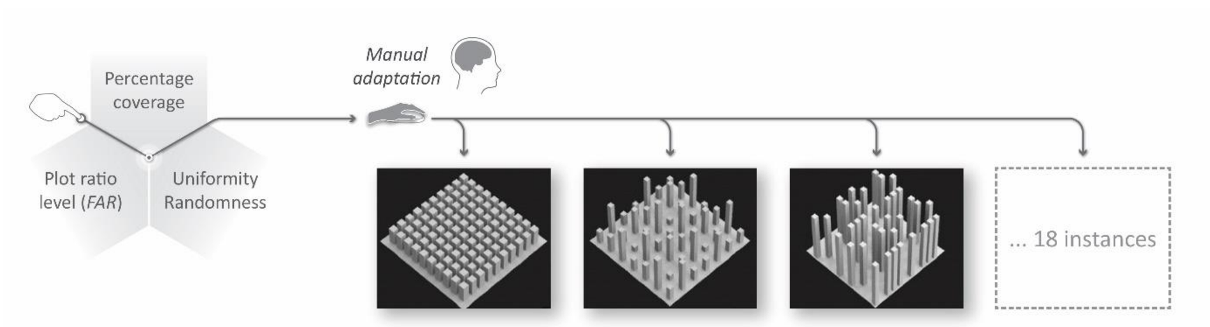


Fig. 80. The process of manual assembly for instance models, starting from the abstract intersection of input options (source: author).

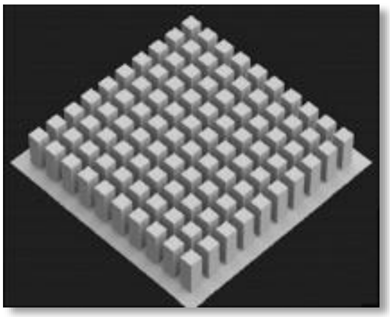


Fig. 81. Case 5 – Layout: U, U; site coverage: 36%; plot ratio: 3,6.

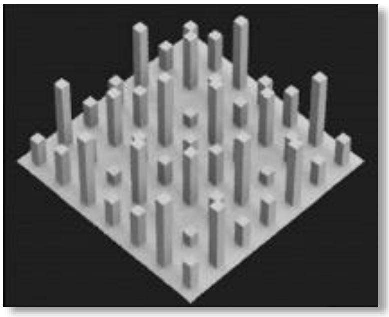


Fig. 82. Case 7 – Layout: U, R; site coverage: 9%; plot ratio: 1,4.

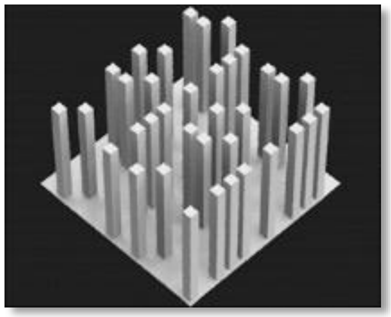


Fig. 83. Case 14 – Layout: R, U; site coverage: 9%; plot ratio: 3,6.

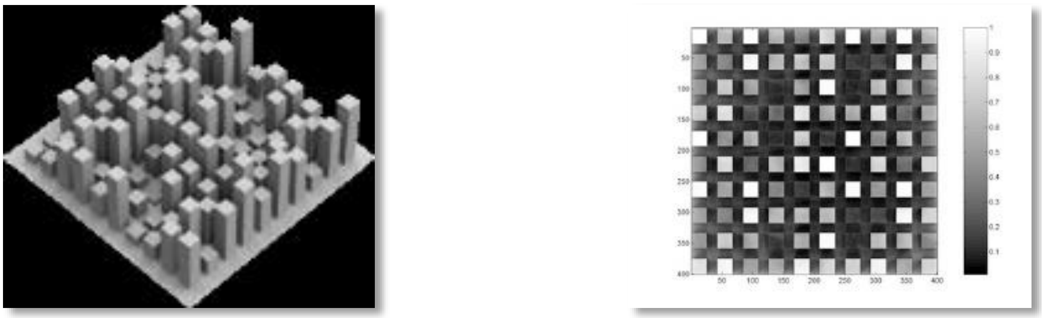


Fig. 84. Case 11 – Layout: U, R; site coverage: 36%; plot ratio: 3,6. View of instance model as a *DEM* (on the left), and appraisal in terms of daylight availability, carried out in *PPF* (on the right) (retrieved from Cheng et al., 2006).

As *DEM* consists in static (*additive*) instances, the generic models of this first study can only support a straight-line assessment practice, implying the *ex-post* simulation of their energy performance through specialized software. One by one, the eighteen models undergo simulation with *PPF*, a radiance-based tool using Monte Carlo ray tracing methods for its calculations (Cheng et al., 2006). The energy dimensions chosen for such "separate" simulation environment mirror three criteria for appraising geometric qualities: *1*) openness at the ground level, measured in terms of *Sky View Factor*; *2*) daylighting provision, measured through *daylight factor* on building façades; *3*) solar accessibility, measured as *photovoltaic potential* on building envelops.

The first, we repeat, describes the extent to which solids obstruct the view of the sky from a surface, and along a normalized scale too: a *SVF* of 1 means an unobstructed view of the sky, while a SVF of 0 means a completely obstructed view of the sky. Considering the ground level as the locus of observation points, the sky view factor has proven to have close relationships with the distribution of ecological phenomena such as heat island effect, air pollution and surface energy budget (Oke, 1981; Svensson, 2004).

Within the realm of this research, the second and third indicator follow specific mathematical meanings. Daylight availability on façades is defined, here, as the proportion of global illuminance captured by façades, which results from sunlight, skylight and reflected light, to the global illuminance harvested by an unobstructed horizontal plane[105] (Cheng et al., 2006). In parallel, researchers set definite targets for detecting solar potential for photovoltaic systems (PV) within a sound perspective of unambiguity. In this case, photovoltaic potential depicts the percentage (%) of building envelop that receives an amount of solar radiation greater than or equal to preset thresholds: 800 kWh/m^2 for building façades and 1000 kWh/m^2 for roofs[106].

[105] As daylight availability changes in relation to sky models that vary from a place to the another, the research considers such measure under average annual sky conditions in Sao Paulo, as this sky model had been developed for solar simulation in a prior study (Cheng et al., 2006).

[106] Both values are determined based on technical limitations as well as economic considerations discussed in Compagnon (2000).

3.1.1. *Technology* – Parametric only in the approach, with no algorithmic and computational support: the restraints to input quality and the separation between form and evaluation

This case lies on the first tier of our technology layer of interpretation. The application happens to be parametric in the approach, but in reality, a number of fallacies undermine the significance of results. First, we do not see any digital algorithmic support to the assembly of an abstract matrix, despite the inherently parametric essence of variation system. The reproduction of concrete instances is utterly on behalf of human elements; that being the case, accidental errors may occur, at least to a certain extent, when shifting from a parametric configuration to the other. Besides, every move between one output instance and the other equally requires consistent efforts in managing the material assembly of compositional hypotheses. In other terms, we do not manage those ghost geometries that characterize truly *associative* behaviors within a digital parametric environment.

Another important aspect of this layer consists in the connection pattern between design and evaluation circuit. Case A is dominated by a strict separation of evaluation phase from shaping endeavor, due to the intrinsically restricted scope and opportunity space of *additive* and non-algorithmic logics. This in spite of the whole effort in matching precise parametric options with corresponding instances. The need for external software is nothing more than the negative of this paradigm. The design of DEM instances requires, in this case, both the incorporation of data about randomness, and the subsequent export to the evaluative platform[107]. This is translated to scarce integration of workflow and a constant need for packing and unpacking the model across the two environments. In synthesis, there is no real-time appreciation of parametric *feedbacks* on performance. Above all, we consider the need to repeat evaluation per each model against each criterion, which leads to the multiplication of time, effort and cost, as overlaid upon the static nature of instance models. The general ease in combining inputs within a simple and intuitive matrix for human mind is discounted by the relative friction in obtaining a "fluidized" and straightforward process of interactive valuation.

The hand-made flavor of this parametric environment also affects the significance of input in determining the gradient for exploration and, by consequence, both reliability and quality of results[108]. First, parameters chosen in the model have *discreet* values: for example, 1,4 for *low*, 3,6 for *medium* and 7,2 for *high* density. Intermediate shades of density are not contemplated, as these would be prohibitive in a context of manual adaptation. Besides, values are also limited in grain and extent: the range from 1,4 to 7,2 m^2/m^2 is quite large, but thresholds are only three. Even *randomness*, despite being computed through *Excel* as an automatic informer of "out-of-the-box" shapes, shows a problem: it runs *once* per each concrete instance where irregular layout plays a role. In other words, each random layout is attached to one, rather than more seeds of random coordinates, meaning that output models that undergo evaluation are only a partial quota of how many they would actually be with a digital algorithm. An algorithm that could save a chance for shifting from a seed to the other. This amounts to a loss in the level of governability of spatial display within the sample, which, together with the admissions of researchers (Cheng et al., 2006), leads us to assume that we deal with a restrictive tool in addressing design practice. Embodying the outcome reflections surging from this understanding would most probably represent a highly discretionary risk, due to not only the atopic setting of the experiment, but to the restraints in defining inputs as well.

[107] Which of course has to be one able to read *DEM* output format properly, otherwise an additional adaptation would be required. In this case, *PPF* is explicitly programmed to import *DEM* formats directly.

[108] This reasoning comes from the awareness that the forcefulness of outcome information stems from the supply of high-resolution data more than the exclusive validity of methodological processes.

3.1.2. *Expendability* – The parametric independence of horizontal and vertical obstructions: a combinatorial chance for urban form to increase densities with no expense for energies

The human restrictions observed through the technology lens entail a clear limitation to one elementary type, in this case the single house/tower, which does not give back a wide-ranging management of urban complexity. Scenarios are expressed through the aggregation and repetition of the same type, which, in turn, preserves the same size. This also means that we do not detect any combination of the same types into composite and variable structures, due to the inertia of conventional, manual and *additive* design of correlation patterns.
However, we can still appreciate a relevant effort in granting the conceptual *independence* of input parameters. Despite the absence of a verified algorithm, the case guarantees a well-defined self-consistency of each development scenario. In fact, as an example, coverage does not fall into mutual conflict with floor-to-area ratio nor with horizontal/vertical randomness.
Despite the use of site-specific data for carrying out energy analysis[109], spatial setting, other than being a perfect square, remarks a fully isotropic development site. The research consciously conceives no distortion, as it chooses to focus on comparing generic samples. In addition, each building unit is exclusively oriented to South. With respect to the relational patterns established between shapes and densities, we observe a perfectly parallel configuration system, as both insist on the final instances in guise of changeable inputs, thus springing a considerable opportunity space for outcomes to emerge. This sort of combinatorial opportunity set, as we will see in detail through the following lines, proves to lead to a strategic increase of urban densities for the future of anthropic environment, due to the substantial amortization (or even drastic inversion) of energy maluses[110].

[109] Inherited from the wider research project carried out for Sao Paulo.
[110] Something that seems to recall a *Pareto-optimal* tension, where space represents the *Edgeworth box*, while density and energy performance lie on hypothetical *utility curves*, expressing the *locus* of points with constant ranks of such measures. In this light, we could imagine that flowing through a parametric domain may unlock the transfer to higher utility curves of density while still insisting on the same (if not higher) utility curves of energy. Beyond Pareto-optimality, we'd assist to further increase of densities without making energies better-off anymore; rather, it would result in detrimental effects.

Plot ratio	Site coverage	Form (H, V)	Sky View Factor	Daylighting	Solar potential
1,4	9%	U, U – Case 1	0,32	0,33	6%
		U, R – Case 7	0,40	0,35	8%
		R, U – Case 13	0,43	0,33	6%
		R, R – Case 16	0,50	0,35	7%
	36%	U, U – Case 4	0,20	0,27	17%
		U, R – Case 10	0,30	0,29	18%
3,6	9%	U, U – Case 2	0,17	0,22	2%
		U, R – Case 8	0,26	0,30	3%
		R, U – Case 14	0,32	0,25	3%
		R, R – Case 17	0,36	0,30	4%
	36%	U, U – Case 5	0,11	0,15	8%
		U, R – Case 11	0,18	0,18	5%
7,2	9%	U, U – Case 3	0,11	0,17	1%
		U, R – Case 9	0,15	0,21	1%
		R, U – Case 15	0,27	0,22	2%
		R, R – Case 18	0,30	0,24	2%
	36%	U, U – Case 6	0,06	0,08	4%
		U, R – Case 12	0,09	0,13	2%

Tab. 3. Matrix of output values connected to the geometric profiles under scrutiny (retrieved from Cheng et al., 2006).

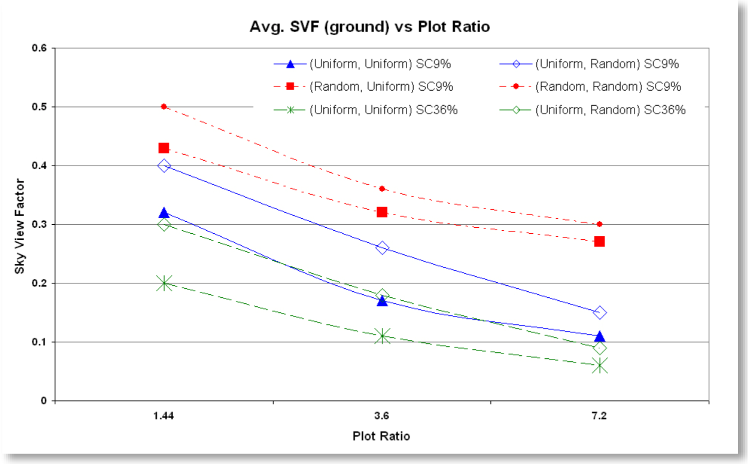
Findings for ground openness

As a general trend, we recognize that the *Sky View Factor* shrinks with increasing coverage and plot ratio, due to the proliferation of, respectively, horizontal and vertical obstructions: spreading more units and/or building higher tends to narrow down the observation of sky vault at ground level. Anyway, results show that intersecting the increase of densities with certain shapes does have an influence in aggravating or mollifying the openness of void systems. Even considering models within a single class of plot ratio, that is, models providing the same amount of floor area, randomness plays a big role in lessening heat island effects related to the geometry of built environment. The parametric shift from regularity to randomness sheds light on a comparative consideration of random layouts as preferable to uniform layouts. Also, horizontal randomness proves to be a stronger determinant compared to vertical randomness across the whole gradient of densities, while vertical randomness acquires importance at higher density pressure, hinting that it may serve as a "decompressor" for concentration. Thus, the improvements with vertical randomness are extremely valuable in terms of spatial efficiency, though less impressive compared to horizontal randomness.

The report figures out that, for models with 9% site coverage, the increments in *SVF* from horizontal uniform and vertical uniform (U, U) to horizontal random and vertical uniform (R, U) are 34%, 88% and 146% respectively for low, medium and high plot ratio. Instead, the gains from horizontal uniform and vertical uniform (U, U) to horizontal uniform and vertical random (U, R) are 25%, 53% and 36% (Cheng et al., 2006).

We can observe, as a general picture, that the improvements obtained through (R, R) settings have a significant order of magnitude, if compared to (U, U): 56%, 112% and 173% respectively for low, medium and high plot ratio. This seems to suggest that matching both horizontal and vertical randomness with higher densities tends to be more beneficial than what we could gain crossing random layouts with lower densities. Also, comparing sky view factor between high-density random models (for example, cases 17 and 18) and low-density uniform

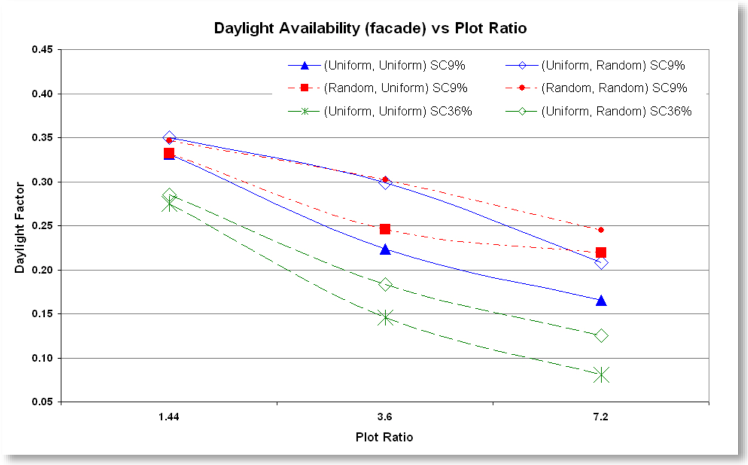
models (for example, cases 1 and 4) unveil the chance to preserve or even augment ground openness although pressuring urban space with higher amounts of floor areas (Cheng et al., 2006). The two low-density instances have SVF values of, respectively, 0,32 and 0,20; while the other two instances, though denser in terms of plot ratio, show values of, respectively, 0,36 and 0,30.
The effect of site coverage, independently from plot ratios and random options, suggests rather straightforward interpretations grounded on a clear connection between coverage and frequency of volumes obscuring the view of the sky. Models with 36% site coverage see less sky at ground level than those with 9% site coverage, with no exception for instances having lower building heights.



Gra. 2. Plotting the eighteen instance models in relation to average *Sky View Factor* at ground level (*Y*-axis), compared to plot ratio (*X*-axis) and based on assorted solid-void settings (retrieved from Cheng et al., 2006).

Findings for daylight availability

Increasing density in terms of either plot ratio (building higher) or site coverage (adding blocks) has equivalent implications on daylight access for building façades, due to the growing spread of obstructions. This is true for the average picture, but still, we can investigate the detail of shape-density mixtures to draw hints for a mindful compromise.
For instance models with 9% coverage, the increments in daylighting from (U, U) to (R, U) are 0%, 13,6% and 29,4%, corresponding to low, medium and high plot ratio. The results demonstrate that horizontal randomness seems not to imprint noteworthy effects at low densities; yet, we can notice a growing influence toward higher densities. Conversely, the impact of vertical randomness is significant through all classes of plot ratio, though still most prominent at higher densities: the increments from (U, U) to (U, R) go from 6% to 36,4% and 23,5% respectively for low, medium and high plot ratio.
However, the overall improvements confirm that, together with the behavior observed for SVF, randomness is most beneficial in high-density environments: from (U, U) to (R, R) layouts, we appreciate increments of 6%, 36,4% and 41,2% respectively for low, medium, high plot ratio (Cheng et al., 2006).
Looking closer to results at high plot ratio, we may interpret both horizontal and vertical randomness as powerful instruments for improving daylighting a lot simply by means of alternative configurations of shape, without renouncing to the original floor area (Cheng et al., 2006). The daylight availability on façade with a (R, R) layout and low coverage (case 18) could triple the one obtained with (U, U) layout and high coverage (case 6).



Gra. 3. Plotting the eighteen instance models in relation to *daylight availability* on building façade (*Y*-axis), compared to plot ratio (*X*-axis) and based on assorted solid-void settings (retrieved from Cheng et al., 2006).

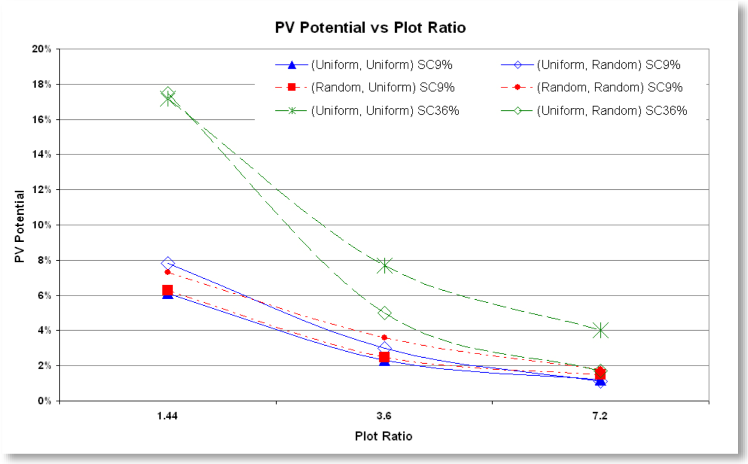
Findings for photovoltaic potential

As a much more demanding requirement, photovoltaic potential seems to partly derail from the design choices preferred in terms of both ground openness and daylight availability on façades, which may lead to reconsider the role of randomness and its relationship with density aspects through further reflection. In reality, this relationship, while depicting apparently clashing perspectives for solid-void systems, will trace earlier suggestions back to a coherent framework, giving due weight to the three dimensions as a whole.

With respect to solar potential, instance models with (U, U) layout and high coverage (cases 4, 5 and 6) perform significantly better than other models (Cheng et al., 2006). Despite this sounds contradictory compared to other measures, the result makes sense if crosschecked with evaluation criteria. High levels of solar potential strictly depend on the exploitation of large and unobstructed roof areas as a condition for effective PV paneling. Such models reproduce a pattern of urban geometries that is highly suitable for PV application, as high site coverage and harsh uniformity translate into numerous roofs that would boast high-level radiation with no overshadowing events whatsoever (Cheng et al., 2006).

Nevertheless, changing site coverage to low unveils the importance of random layout, especially in the vertical direction. As solar potential also considers storing energy through lateral façades, random vertical layout ends up with being a preferable arrangement, because it improves their sunlight access as a compensation for inadequate roof surfaces (Cheng et al., 2006). Horizontal randomness, while being relevant for the other measures, seems not to affect the results very much: this means a lot as well, for no impact equals to *no negative* impact.

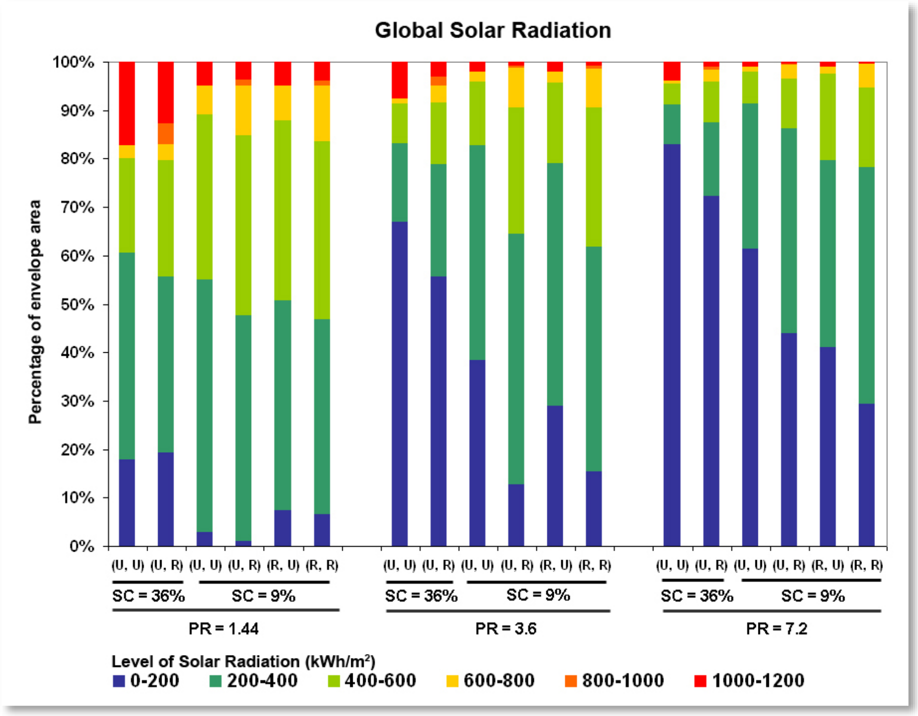
In any case, increasing plot ratio should cope with the inevitable multiplication of sunlight obstructions, which, being typical of compact settings, makes it difficult to meet suitable radiation standards for PV systems (Cheng et al., 2006).



Gra. 4. Plotting the eighteen instance models in relation to *photovoltaic potential* of envelops (*Y*-axis), compared to plot ratio (*X*-axis) and based on assorted solid-void settings (retrieved from Cheng et al., 2006).

As a corollary to solar findings, a frequency study unveils further information upon the breakdowns of global radiation captured by building envelop as a whole, i.e. with reference to both lateral façades and roof surfaces. Such basic figure would help understand the percentage distribution of lower to higher radiation values in each of the eighteen models, sorted as a function of input options.

Two observations can be made in relation to our three classes of plot ratio: one refers to the proportion of low-level solar radiation, that is, from 0 to 200 kWh/m^2; the other refers to the opposite behavior of high-level solar radiation, ranging from 800 to 1200 kWh/m^2. In the first case, we observe that models with high plot ratio have a proportion of low-level solar capture that is substantially higher than that of models with low plot ratio: from 30 to 80% versus 20% and below. But this sheds light on how such proportion may be cut down with attentive design measures, because we understand that low-level radiation reduces with lower site coverage and random arrangements of form. In contrast, the second case urges to reconsider this vision, narrowing the extremism of coverage and randomness. In fact, the proportion of high-level radiation increases with increasing site coverage, in line with the previous observations of PV potential (Cheng et al., 2006). This should not be a surprising aspect, since radiation levels detected in this research are extremely sensitive to zenithal surfaces like rooftops. Moreover, radiation ranges leave room for design options that may adapt to different solar strategies for satisfactory performance. The chart below would enable to estimate the potential of these strategies, based on target values. For example, considering a threshold of about 600 kWh/m^2 for solar thermal collectors, the chart tells us that vertical randomness would be as influential as site coverage to this end (Cheng et al., 2006).



Gra. 5. The frequency analysis of envelop portions (%; *Y*-axis) per range of radiation values (kWh/m^2), carried out for each of the models, sorted, in turn, according to plot ratio, coverage and pattern (*X*-axis) (retrieved from Cheng et al., 2006).

Synthesis of findings

In short, we can appreciate the contribution of randomness in arranging performing arrangements, particularly at higher plot ratios. Random layouts are, in general, beneficial. Still, we can distinguish diverse benefits across several ways of intersecting randomness with other conditions to development (Cheng et al., 2006).
If we take into account both ground openness and daylight availability, randomness is more beneficial in high-density settings than low-density settings. Horizontal randomness is more influential than vertical randomness for ground openness, but its influence changes according to plot ratio from a daylight perspective: in low plot ratio settings, it has a minor or even negligible impact; such impact only acquires significance in high plot ratio setting. Conversely, vertical randomness is influential in all cases, though always proportionate to plot ratio as well (Cheng et al., 2006).
In turn, randomness seems to manifest an alternate pattern of influence for photovoltaic potential: while horizontal randomness does not yield any significant impact on PV performance, the effect of vertical randomness differs according to site coverage (Cheng et al., 2006). High site coverage arranges form to gather radiation to larger extents, but only if connected to vertical uniformity; random heights would prove to be disadvantageous in this kind of settings, due to the proliferation of overshadowing effects on roof area. As we ponder the benefits of low site coverage for the other two measures, PV potential may come to a coherent framework of compositional preferences, for vertical randomness, in this case, becomes advantageous to better solar access on lateral façades. Dramatizing site coverage and uniformity would provide extensive roof surface as a major source for high-level solar radiation, which is advantageous for PV application. Nevertheless, we should consider offsetting this hypothesis through lowering occupation, so as not to undermine daylight and solar potential on ground and building façade (Cheng et al., 2006).
But the most promising suggestion of this study consists in confirming a general hypothesis that, moving from prospects of efficient occupation of space, conceives the permutation of geometries as a stratagem for matching a compositional balance. In fact, results show that, at least in terms of openness, daylighting and solar potential,

designers may achieve significant improvements by simply reorganizing block patterns, with no necessary cuts to usable floor area. If we compare proper layouts at high plot ratio with improper layouts at low plot ratio, we get to understand that it is possible to increase floor area while preserving, and sometimes reducing the distance to performance targets. Within the same class of plot ratio, the order of magnitude of such improvements from the "worst" to the "best" layout reaches the entity of 100 to 300%[111], which challenges the conventional assumption that "pressuring" urban space with higher densities would end up with the deterioration of sky views and sunlight access (Cheng et al., 2006).

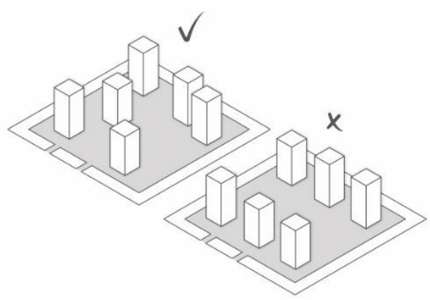


Fig. 85. One, the research endorses randomness in horizontal layout. Given the same class of plot ratio, it is preferable to arrange units in scattered, rather than regular patterns (elaboration from Cheng et al., 2006).

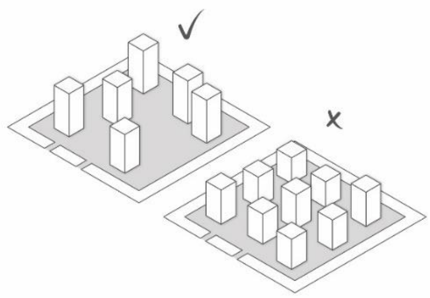


Fig. 86. Two, arrangements with taller buildings and less site coverage are more desirable than those obtained with lower buildings and higher coverage, especially for a matter of daylighting (elaboration from Cheng et al., 2006).

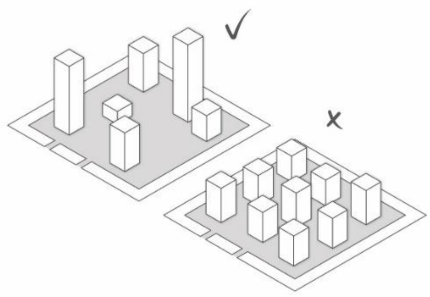


Fig. 87. Three, randomness in vertical layout shall also be encouraged, particularly in a framework of low coverage, for increasing sunlight access on building façades (elaboration from Cheng et al., 2006).

The study points out that governing form parametrically as an intersection of shapes with densities may unveil some appreciable clues for planning high-density solar cities. In particular, conceiving patterns of urban environment as explicit functions of basic parameters may help explore alternative ways to compaction, departing from conventional assumptions regarding high coverage, clumping buildings or even scarce open spaces.
In other words, densification may not necessarily end up with undermining potentials for daylighting in buildings and PV applications on building façades (Cheng et al., 2006). Rather, rearranging the design of geometry would provide the same amount of usable floor area while potentially resulting in better daylight and sunlight potential. This is a crucial point for our "philosophy" of spatial efficiency: it is important and desirable to find solutions hinting that the intention for densification and the concept of sustainable development are not mutually exclusive, and that compact cities, given well-reasoned urban design, can be a respectable solution to rapid urbanization and urban regeneration challenges.

[111] Except for daylight availability at low plot ratio.

3.1.3. *Complexity* – The discovery of randomness factor as a principle for solar cities explains the influence of reductive constraint systems in determining the quality of solutions

Given the inherent flaws of input definition[112], perhaps we should spend some time judging the complexity of outcome forms, as these, being a direct consequence of such restraints, are generally connected to the reliability of findings. In this perspective, we understand *propagation effects* to be something not pledged to the simplistic flavor of automated modeling, but rather, something that implies bigger awareness of how we, as human components, define the structure of raw data for meaningful and well-designed parametric systems. Having a look at the "complexity layer" would mean estimating the possible distance of outcomes from realistic urban design expressions, or, in other words, the extent to which modeling products are simplified compared to the morphological scope of composition. This further interpretation may disclose a clearer outlook on the significance of samples as materials for design suggestions, because reasoning upon realism would make explicit reference to "where" we need to go for an accurate picture of efficiency conditions; conditions that would be grounded on a context of complex equilibria. We will see that this sounds much less "byzantine" as we go through what the concrete case shows in this respect.

We know that this first case (*A*) allows for changing both density and coverage ratios as parallel and independent conditions, despite the inevitable limitation to their scales. Yet, we have to recognize that these parameters, while acting as multipliers of occupation, define specific form only in connection to the block type chosen and the distinction between uniform and random array, combined to either or both horizontal positioning and vertical diversity. Let us consider the horizontal layout first: in case of perfect regularity (U, U; U, R), we observe an isotropic distribution of bulks, where spacing follows a fixed extent that varies proportionately to site coverage in all directions. In other words, a regular distribution is restored at any change of covered ratio. Within a context of "quick escalation" between strict uniformity and unbridled randomness, this means that we cannot expect any mixture of uniform/random settings, nor their concentration/decentralization tendencies. These aspects could characterize, instead, real-world situations in which more or less organized patterns tend to interact with each other on the one hand, and to (re)distribute more or less conformably on the other.

Submitting to randomness as the sole element of distinction for urban patterns seems to exclude a more precise "patchiness" of single locations, which may represent, instead, a factor having some influence on real-setting performance. This also applies to vertical occupation: we cannot govern it unless we submit to either an erratic degree of randomness, which may yield wide spectra of different results against energy measures, or an overly simplified, but deterministic isotropy. This aspect serves as an example of how decisive can be the link between definition of inbound data, nuance of association rules and consistency of outbound values.

Real-world solutions are made out of another class of distinctions, based on inter-relating geometries of occupation: namely, typologies. In this case, we contemplate one elementary typology, that is, single house or tower on square footprint, with no actual chance for combinations or cross-type musters whatsoever. Besides, we see no changes in sun orientation: all units and patterns have the same South-facing layout. In reality, square-based types are not sensitive to orientations, due to their equal-side property. However, results may vary if we simply rotate or invert their patterns altogether; for instance, from South to North or East to West, and *vice versa*.

Typology is not at all a subordinate aspect of performing environments. Actually, site coverage and plot ratio, which do have a role in determining energy measures, cannot be set apart from the typology used, and square-based single houses/towers only represent one of the possible ways of relating such inputs to end performance. Arranging combinations of one typology or even mating patterns of different typologies may lead to staggering conformities between the amount of coverage and plot ratio suggested for particular targets, and actual results in terms of energy measures, which may submit to more or less relevant oscillations.

[112] Which we recognize as inevitable curbs for a manual approach to "parameterized" modeling.

For example, the preference for low coverage and randomness is supposed to foster vertical solar paneling, but it results from barring all types except single houses/towers, which have limited and fixed roof areas. It follows that, according to this definition, we do not know if other kinds of type geometry (either present or future) may manifest the same demand of horizontal and vertical randomness for seizing radiation. For instance, let us take city blocks as a typology that diverges from single houses/towers at least in terms of pure geometry. Structuring built environment as an array of courtyards would articulate a different solid-void configuration, where carved and filled spaces, arranged as alternate elements, might reach comparable solar targets through flat roof extensions while relating differently to decisions made for coverage, plot ratio and degree of randomness.

At this point, it seems clear that randomness, while being a manageable and one-off input for manual modeling, implies very low governability and information for guiding more precise occupation choices, both horizontally and vertically. In fact, it gives no clue about neither scale nor spatial dissemination of changes from a regular distribution of heights and surfaces. As we presumed at the beginning of this section, this is a direct implication of scarce computational support, or, in other words, a necessary compromise with the inherent restrictions that characterize manual, *additive* modeling. Conversely, a digital-algorithmic application perhaps would embed a refined definition of input data, such as diverse geometries and options of occupation, keeping up with a direct automatization of instances at the same time.

3.2. Case *B* – Using *Grasshopper* for generating sample patterns through a definition of building typologies and their spatial ordering principles for efficient occupation

The second case study moves from the consideration of geometric properties and urban densities, respectively design choices and economic factors of pressure, as determinant attributes for curbing neighborhood efficiency in terms of land use and energy consumption (Yunitsyna & Shtepani, 2016). The research consists in exploiting *Grasshopper*'s potential in propagating the impacts of a design choice based on satisfaction of a rule of thumb. This passage is particularly important, because the intersection between two or more alternative options and a shared condition for spatial arrangement permits the evaluation of differing occupation patterns on a comparative layer of "pure performance", where forms expose their own reactions to the same treatment net of superfluous judgements.

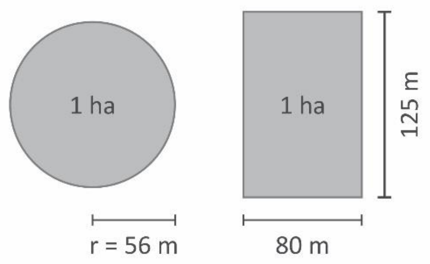


Fig. 88. The two development sites under examination, leading to two different arrangements: circular (on the left) and rectangular (on the right); both sites share the same area of 1 hectare (source: author).

The reference system of this case study is still atopic, but it splits into two possible "twists" of a perfect square: a *rectangular* site and a *circular* site. Both sites are Rhino geometries sized to 1 hectare each[113] and vowed to the accommodation of building arrays forming basic samples. The patterns lie on preset and accustomed urban typologies rising from curves embedded as input primitives (Yunitsyna & Shtepani, 2016). Curves depict types having width always fixed at 14 meters. Every type is specifically designed as an alternative occupation logic. The first type represents a single house or tower, with an extent of 14 x 14 meters; the second type represents a row house, with an extent of 14 x 50 meters; the third is a city block, whose side is set to be not smaller than the double of its width, plus three times the number of floors. Aside from input curves, which play as informers of horizontal occupation, we can introduce the sole input parameter of the system, which plays as an informer of vertical occupation through the number of built storeys. Such parameter is a *Grasshopper* component in all and for all that is set up in guise of a slider ranging from a minimum of 1 floor to a maximum of 10 (Yunitsyna & Shtepani, 2016).

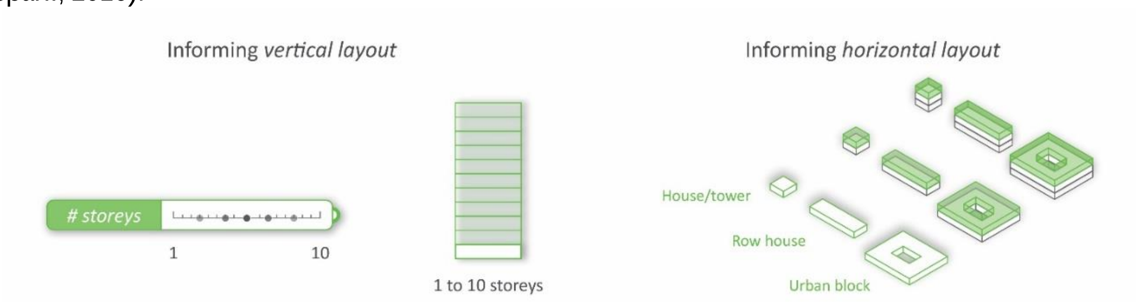


Fig. 89. The two inputs, one for *vertical* and one for *horizontal* layout. Vertical layout in informed through a parameter governing the number of generated floors, which is applied to all units; horizontal layout can be distinguished with different input curves, one per each typology (source: author).

[113] Precisely, the rectangular site stores morphological development within the extent of 80 meters along *X* and 125 meters along *Y*, while the circular one within the radius of 56 meters (Yunitsyna & Shtepani, 2016).

Here, the assembly of inputs into an abstract matrix consists in furtherly instructing horizontal layout of generic samples, so that spacing regimes depend on floor numbers. The criterion used is the minimum solar obstruction angle of 45°, which entails that propagation travels from heights to equivalent void widths[114]. Both horizontal and vertical constraints are designed to apply to all typologies, based on intents of pure performance. As such, the abstract matrix yields an amount of 60 concrete instances, resulting from three geometry options, two sites and a range of ten floors (Yunitsyna & Shtepani, 2016).

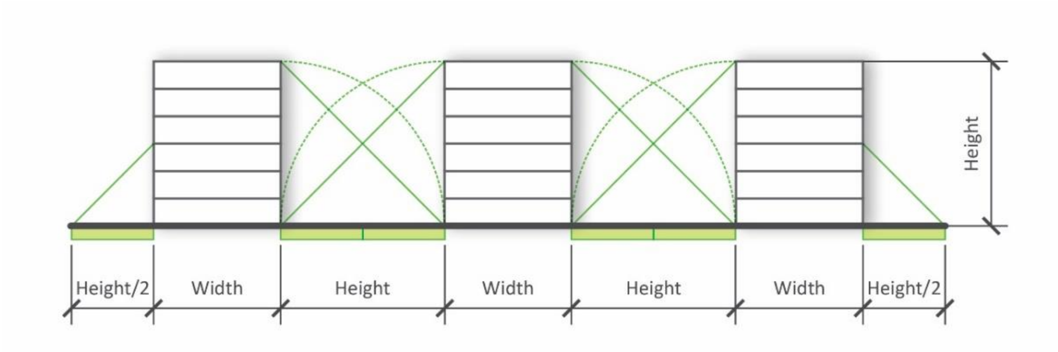


Fig. 90. The rule of thumb used for imprinting pattern generation: any increase in vertical layout shall correspond to proportionate horizontal voids, so as to guarantee a minimum solar obstruction angle of 45° (elaboration from Yunitsyna & Shtepani, 2016).

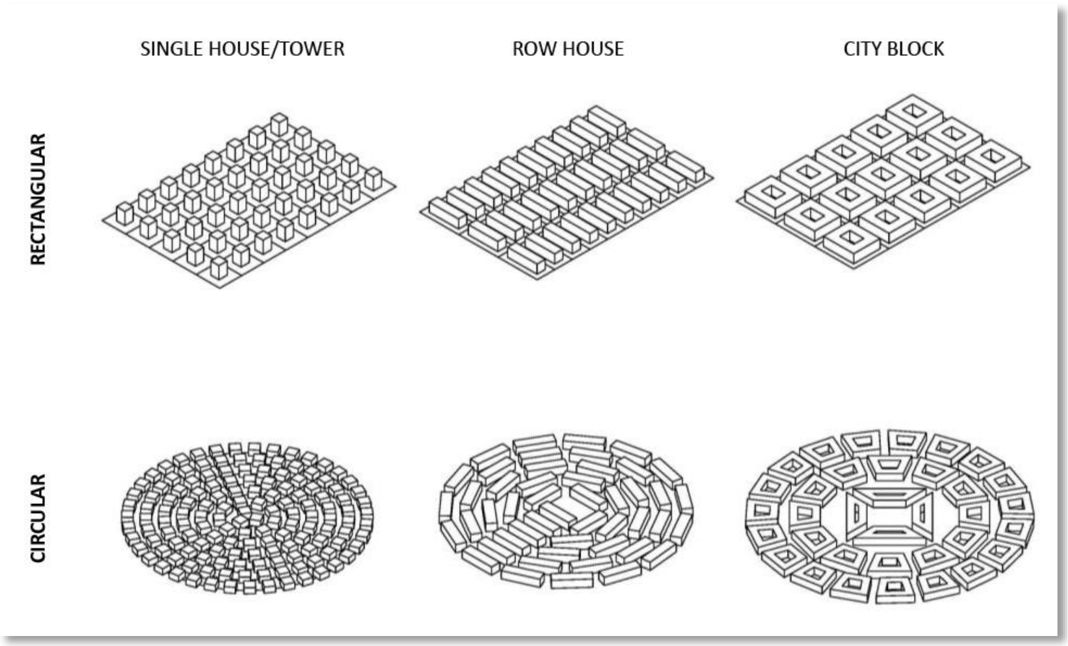


Fig. 91. Samples representative of the 6 urban patterns generated through the algorithmic matrix; spacing corresponds to the heights we see; the total number of instances is 60 (6 x 10 floors) (retrieved from Yunitsyna & Shtepani, 2016).

The evaluation of such "gradient" of instances is carried out through indicators composed as custom branches of the algorithm, just like the previous constraints, so as to match outcome patterns with measures of efficiency at every change of input type and every increment (or decrement) of floor number. These output indicators can be discerned into two families: formal and energy implications of typologies. Among formal implications, we find three measures: *1*) *building density*, which is expressed as floor-to-area ratio; *2*) *number of building units* generated as a consequence of both input settings and solar rule of thumb; *3*) *site coverage* (%). In parallel,

[114] As an ancillary condition, researchers set minimum spacing between outward buildings and site perimeter at half their height (Yunitsyna & Shtepani, 2016).

we have two additional indicators pertinent to the energy implications of patterns: *4*) *compactness* or *shape factor*, which is nothing more than the quota of envelop surface in square meters per cubic meter of volume (surface-to-volume ratio); *5*) *solar radiation*[115], which corresponds to the total amount of kW received by all envelops in one year.
Through the paradigm of *forward design*, based, in turn, on manual alterations of parameters and input geometry, researchers propose to collect and plot comparative trends of typological arrangements against the battery of output indicators, traveling along the input scale of 1 to 10 floors.

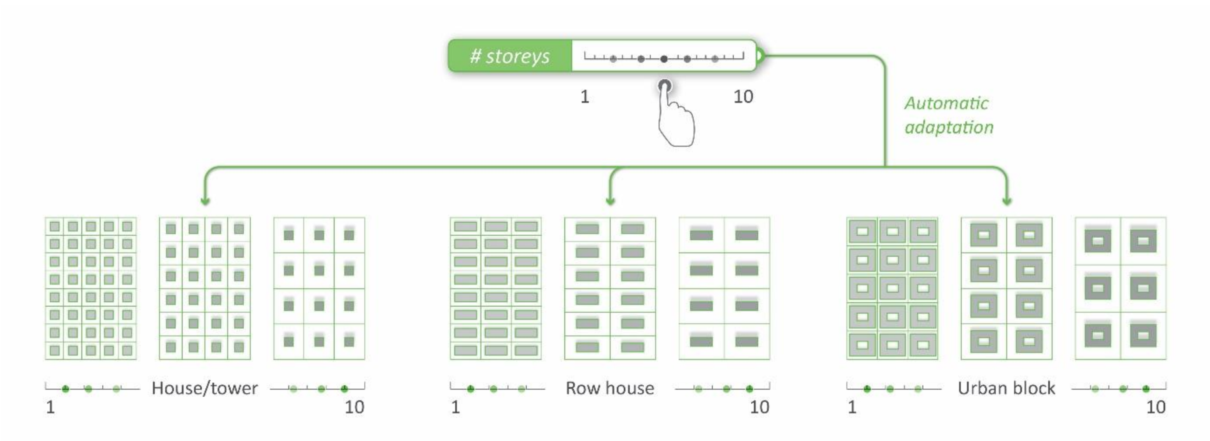


Fig. 92. The *autopoietic* nature of the abstract matrix, based on the intersection between # of floors as the input parameter, input curves for typologies and spacing rule of thumb, supports *forward modeling*, starting from the management of input and leading to *linear* preview and evaluation of concrete instances (source: author).

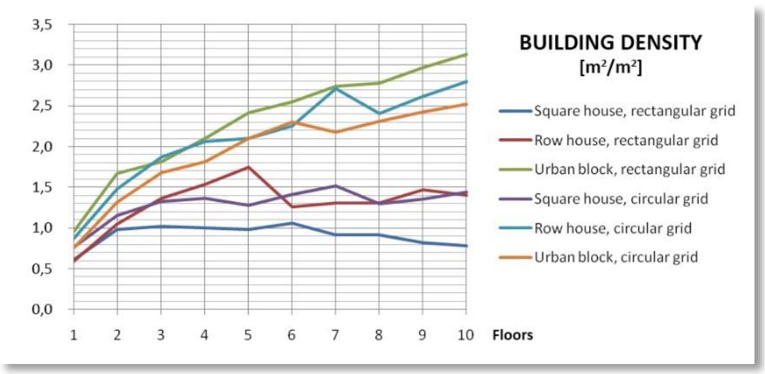
3.2.1. *Technology* – Leveraging the computational support in its *linear* option: the automation of instances and the propagation of changes through embedded evaluators

Unlike case *A*, this study makes full use of an algorithmic support. Here, we assist to its *linear* option, that is, forward design, which produces an array of self-consistent "roads" to the output. Direct permutation of design schemes can be achieved through this abstraction. Human element defines the procedural matrix, but not anymore the sequence of its single instances. Besides, design inconsistencies do not reside but in the construction of a constraint system, which of course requires to be checked in terms of internal coherence.
At least with reference to the calculation of solar potential, we do not observe any reliance on external software, due to a compound and custom use of *ad-hoc* components (*GECO* plugin) within a composite and "feedback-laden" algorithm. The incorporation of a set of evaluative indicators within formal parametric change describes a simultaneous *responsiveness* of performance measures per concrete instance, with considerable cuts to analytical costs.
The *variation* structure of algorithmic inputs allows for *unambiguity*. This is, let us remember, a primary requisite and, at the same time, a warranty of rule observation. Quite the same applies to instructive constraints of *correlation* pattern. These are user-defined bonds, just as we see in case *A*, but this time we assist to a constant *propagation* through transient instances, both for rectangular and circular patterns. Specifically, now users do not have to stick to definite and *discrete* values, but they "*slide*" across a *continuous* sequence of values within an arbitrary and specified range.

[115] Calculated with Autodesk *Ecotect*. We do not consider *Ecotect* as a right and proper external software, since real-time connections with *Grasshopper* can be established thanks to the plugin *GECO* (available at http://www.food4rhino.com/).

3.2.2. *Expendability* – The comparison of different urban types on a "pure performance" level, with the use of solar angles and the rough twist of orientations in round arrays

Through digital modeling based on Rhino + *Grasshopper* environment, researchers define three different urban typologies: single house/tower, row house and city block, each with its footprint boundary imported as an input curve. The expansion along the axis of typologies, despite not so in line with the freeform philosophy of general parametric theory, does represent a sharper articulation of geometries, which serves to appreciate their different effects on spatial efficiency. The outcome environment merely represents an aggregation of the same type, but it is multiplied times three, thanks to the support of *associative* dynamics. Moreover, we experience the automation of a *circular* pattern, which represents a quite interesting approximation of grid distortion as an alternative to stereometric layout.
Types are tested as *responsive* to a precise ordering principle, a *user-defined* one of that, which is not anymore governed by the dichotomy randomness/regularity[116]. Spacing here is normed by how every type reacts to a marginal increase in floor number (vertical occupation), following their perimeter properties (horizontal occupation). Automating propagation reflects precision and unambiguity of spacing regimes. The criterion of minimum solar angle, aside from being a custom constraint that would have required a lot more time and accuracy with manual labor[117], proves to be useful for intersecting densities, shapes and conditions for solar access. This with an attention to the "pure performance" of ideal typologies, within both a perfectly rectangular and circular pattern.
Similar to case *A*, the two sites are isotropic as well, since we do not assist to distortion, except for a rectangular and, thus, slightly more frequent configuration in the real world. It is difficult to imagine a circular application, but at least we could appreciate a rough situation of distortion with reference to twisted geometric choices, due to typically geographic limits. In rectangular patterns, we recognize South to be the only orientation of building arrays, independently from single types. The *quid plus* here lies in circular allocation, which gives a wholesome picture of all the different orientations for each of the three typologies.
With respect to relationships between shapes and densities, we assist to a mutation at conceptual and algorithmic levels. The array of input data is now restricted to the number of floors, i.e. a select declination of density, actually a formal impact on vertical obstruction layout. This aspect alters both residual metrics of density and morphological measures of occupation efficiency. These tend to differ according to both geometric characters of single types and their propagation patterns, which in turn undergo regulation by solar-angle constraints. All the following graphs are retrieved directly from the original research paper (Yunitsyna & Shtepani, 2016).



Gra. 6. In general, city blocks end up with the highest increment in floor-to-area ratio, together with circular row houses. Rectangular rows describe an evident increase up to the 5th floor, a "peak" beyond which density decreases due to the need of adequate spacing.
Square units show the scarcest density, it even decreases with rising vertical layout.

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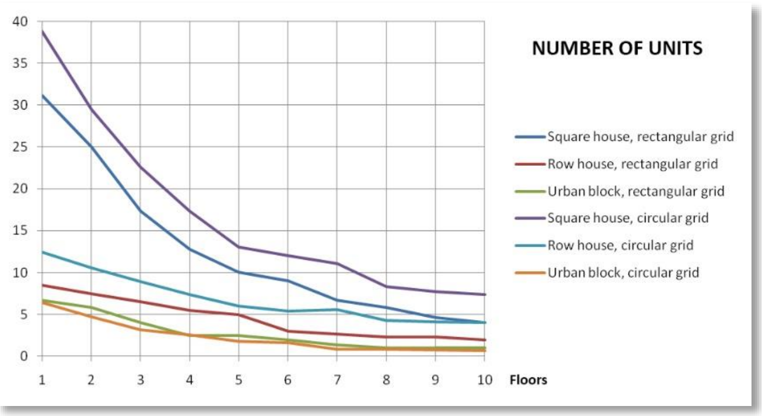
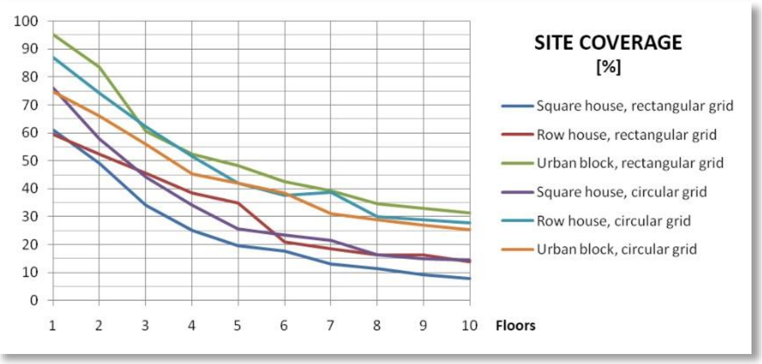
116 A dichotomy where default regularity only depends on equal spacing determined by site size, type extent and covered ratio input.

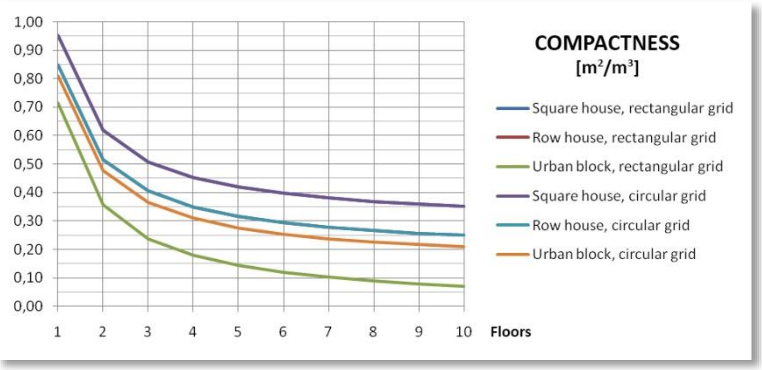
117 Especially if we think of concentric patterns taking place upon circular site, which would require calculating angles of rotation at each enlargement and restriction imposed by floor number fluctuations. Besides, such constraint would be not even possible with *analog* parametrics as well, unless we found (and controlled) a natural force capable of sifting angles of rotation around an axis thanks to some "magnetic" field.



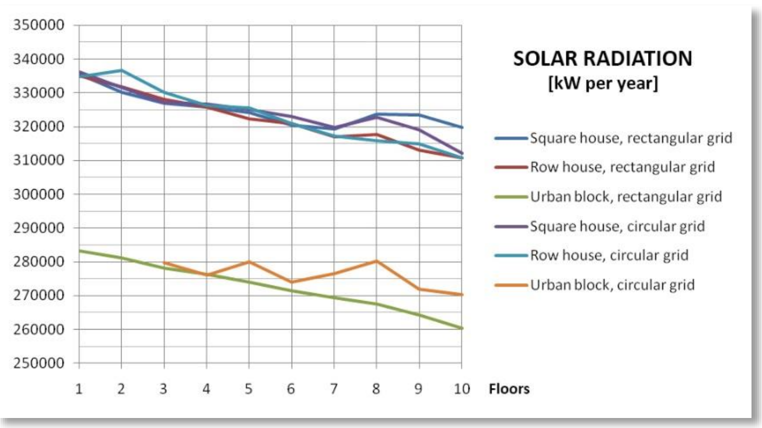
Gra. 7. Fixed borders and spacing rule of thumb constrain all types to a decreasing number of volumes.
Square units show the highest number and the steepest slump at the same time.
Both rectangular and circular city blocks display the lowest number of built structures, but the amount seems relatively stable with its slight decrease, at least considering a 1 to 10-floor range.



Gra. 8. Site coverage is biased with a systematic distortion in circular patterns, due to a central void imposed by the algorithmic definition.
For all types, coverage has a diminishing trend. Lower-rise patterns show the highest ratios of at least 60%.
City blocks show the highest value per increment, while the lowest relate to square houses/towers.



Gra. 9. Square and row houses show, respectively, the same factor per unit, while circular blocks submit to trapezoidal distortions, here evaluated through summative ratio (total surface to total volume).
The highest (and least desirable) factor is noticed for low-rise buildings as a general trend. City blocks show lower ratios, and they perform better in rectangular, rather than circular patterns.



Gra. 10. Values decrease with taller units in all cases with a non-linear trend, which can be explained by the rule of thumb.
It is evident that city blocks show weaker performance compared to the other typologies, due most probably to the complexity of shapes, which causes extra-shading of courtyards.
Between 3 and 9 floors, we can observe a minimal difference in values for patterns of square houses and circular city blocks, respectively.

Engineering typologies toward ready-made urban patterns can provide useful information for picking satisfactory options of horizontal and vertical occupation, with an eye to both socio-economic pressure for density and environmental performance, which would contribute to lessen the energy demand of the city. Screening relationships between building heights, urban typologies and consequent behavior of forms and indicators may be helpful to this purpose.
First of all, the study points out that, at least within the boundaries of this constraint system, it is preferable to organize geometries according to a rectangular pattern, hinting that distortions, which in this case emerge from circularity, have an influence in curtailing the overall performance of built environments[118]. In parallel, we can even notice that conglomerate schemes of occupation, as long as we sustain complex equilibria, may perform better than simpler solutions: at least, this is what we can imagine when comparing aggregations of row houses to square-based ones (Yunitsyna & Shtepani, 2016).
City blocks have a distinctive behavior through the whole set of measures, which seems to suggest the demand of a mindful complexification of forms. Block patterns display the highest building density, but also the lowest number of built units, given the decompression effect of spacing rules; also, they yield the highest site coverage while preserving the maximal compactness at the same time (Yunitsyna & Shtepani, 2016).
Such constant growth of density at each increment of building heights is common only to circular row houses. Conversely, every other pattern succumbs to either decay or stabilization of density beyond the fifth floor. This threshold seems to be a turning point of some relevance even for site coverage, number of units and compactness: all these measures denote sharp reductions until reaching a midway height of 5 floors, beyond which we start to observe only minor changes (Yunitsyna & Shtepani, 2016). Unlike what happens with the latter aspects, upward building heights do not imply particular "swerves" for solar radiation, as it constantly decreases for all the generated patterns. However, while the other types show similar results, city blocks happen to harvest the lowest solar gains by a sizeable margin. This holds independently from site geometry, which leads to suspect, rather, the influence of carved volumes in multiplying obstructive elements as the price for higher complexity.

3.2.3. *Complexity* – The general need for realism in outcome geometry and the overall subordination of solid-void relationships, despite being key implications of urban types

Despite the support of digital parametrics seems to go beyond some of the restraints met in case *A*, we can still detect a gap between models as figures emerging from the constraint system, and the complexity of real-world environments, of course with reference to merely geometric matters. As with the previous study, the simulation draws results from the use of simplified patterns, where factors of distortion like space contraction and variety are not taken into account[119]. Such simplification represents the "margin of error" affecting not only evaluation *per se*, but also the design implications surging from each pattern. Within real urban patterns, the performance is never "pure", unless we deal with an extensive, but alienating repetition of the same buildings in all possible directions. Building units tend to assume complex shape, sometimes by mutation, sometimes by simple aggregation. Distances may vary too. It seems clear that these aspects entail some sort of deviation toward actual or empirical performance.
We have seen that a perspective of pure performance enables the peer confrontation of urban types in reaction to the same *stimuli*, which, in this case, regard floor number and satisfaction of minimum solar angle, the latter being a shared condition for spacing. This rule of thumb is an expedient essential for pure performance, but it also stretches solid-void systems based on the hypothesis that the organization of real urban form is only subject to minimum solar angles; besides, such angles apply the same behavior to identical shapes, ending up with

[118] This judgement is based, clearly, on the sole indicator set included in the research.
[119] This also amounts to other aspects of energy demand that are relevant as well, such as material reflectance and occupant behavior (Yunitsyna & Shtepani, 2016).

improbable and firmly isotropic alternations. While minimum solar angles stand for a common design principle of architecture and planning, the indiscriminate application of such principle would support the assumption of an ever-expanding space devoid of any other force of occupation, which is unrealistic. Types here play a considerable role in diversifying urban patterns. In this respect, we appreciate some sort of complexification compared to the elementary houses/towers of the previous case, for we can manage other two options: namely, row houses and city blocks. Nevertheless, we do not find any room for arbitrary alterations of their root geometries, nor any freedom in testing composite arrays coming from principles of co-existence, deformation or conglomeration. What we can observe is the repetition of one single type per each class of pattern, all with an undifferentiated use of a common and omni-directional rule of thumb.

Finding elements of diversity and specific quality of morphologies would have contributed a lot to the general representativeness of patterns, especially in a case where we can actually see more than one type. Real settings typically twist pure performance, thus compromising further versatility of findings. Perhaps, it would be interesting to intersect energy measures with complementary information, such as factors that usually prompt urban form to the side purposes of an augmented design scope[120]. This would attract some degree of distortion in line with the multidimensional view of composition.

On the contrary, the natural consequence of duplicate forms, together with stubborn spacing rules, is that voids are constrained to be the mere background of types, with no other burden than neutralizing solar obstructions. This is justified as a quantitative appreciation of how far we can exploit available space at each floor increment, but fails in meeting a qualitative interplay of geometries as the expression of other purposes, whose assortment and co-existence typically affects energy performance as well as morphological trends[121]. Assortment and co-existence represent the essence of urban patterns much more than the monotony of multiple copies.

Besides, the picks on diagrams prove the necessity to examine patterns with different heights to find the maximum. From this vertical viewpoint, what we can appreciate is the precise definition of input heights, which is devoid of any recourse to random seeds. However, models do not include any differentiation of vertical change, since all building units behave in the same way.

Last, but not the least, building orientations set up an extra distinction of outcomes in the real world. Here, we observe a clear separation of patterns at the level of site geometry. Though both sites share a South orientation, this property is static for rectangular patterns, which means that all buildings stick to the same angle of rotation, independently from typologies and number of floors. Still, we can credit the study with including a 360° rotation of types within circular schemes, which do constitute a good improvement if we imagine the need to twist types according to irregular (read *realistic*) borders. It is important to note, in this sense, the transfiguration of city blocks from rectangles to trapezoids. However, the global image of distortions, although considering wide-ranging angles, blurs the set of local implications for single units, for all possible orientations conflate into the same, undistinguishable mixture.

[120] Here, we refer to measures that boast some relevance in (re)orienting the organization of built environments, typically pushing solid-void systems toward "out-of-the-box" occupation logics. In our case, we will consider including measures whose benchmarks represent pressure forces for either or both horizontal and vertical occupation. See section 3.4.1.

[121] Like, for example, plot ratio and number of units.

3.3. Case *C* – Trondheim (Norway): identifying residential units through local analysis and unlocking size and inclination of roof surfaces within *Grasshopper* environment

The third case represents the attempt to exploit parameters in the search of morpho-optimal configurations for solar accessibility. As a general "dividing line" between this last practice and the previous two, we can appreciate the *site-specific* essence of its methodological path, for it draws some results from a non-isotropic context, thus managing the morphological efficiency of an actual masterplan. Aside from experimenting the evolutionary optimization of units[122], case *C* commits to an original review of typology itself, suggesting the re-adaptation of native, vernacular houses (Lobaccaro et al., 2016). The experience takes place in Trondheim, Norway, a city that is now under tremendous development in terms of demography and urbanization pressure.

> *«The Norwegian Statistics Centre [or SSB] has estimated that, from [the year] 2000 to 2030, there would be an increase of 70.000 inhabitants. It is expected that this figure will be surpassed due to the fact during the period 2000-2011 the city has shown an even faster growth than the estimated by the SSB center»* (Lobaccaro et al., 2016, p. 869).

This framework pushes to a paradigm able to incorporate renewable energy as an integral part of morphological reasoning from the early stages of district design, so as to efficiently house new residential loads in the prospect of substantial cuts to ecological footprints[123]. However, the Norwegian background on solar energy appears to be biased toward solar potential in high latitudes, which is coupled with the rise of several myths connected to supposedly adverse weather conditions[124] (Lobaccaro et al., 2016). Luckily, a recent study conducted by *Nordic Energy Research*[125] contributed to debunk the hypothesis of a "geographical doom", revealing that the solar radiation received by a track-sun system installed in Sweden equals an identical system installed in Germany. Even though solar technology is still not popular in Norway, results validate the goal of this research and raise the local use of solar energy more and more (Lobaccaro et al., 2016).

The area of Trondheim that has been designated for new development overlaps a part of Øvre Rotvoll, a large greenfield site located in the East between the center and the residential neighborhoods of Ranheim and Charlottenlund[126]. The area of Øvre Rotvoll represents a highly infrastructured, and thus strategic "void" to disseminate new urban population within the borders of existing city fabrics, while providing desirable energy targets such as Net Zero Energy for the new neighborhoods.

[122] Something going far beyond the technology of both case A and B, as we come to deal with *inverse design* systems of holistic search.

[123] A report by the *International Energy Agency* or *IEA* (available at http://www.iea.org/statistics/) states that residential buildings spawn an incidence on total energy consumption that amounts to more than 25%. Decreasing the energy footprint, especially if we consider vigorous urbanization trends, could lead to tangible benefits for environmental, economic and social systems, enhancing their contribution to more sustainable ways of planning and living on Earth.

[124] In particular, the last decades have seen the diffusion of some "prejudicial" debates in Norway (Lobaccaro et al., 2016). For example, temperatures have been considered too low for granting the efficiency of solar systems; in parallel, the solar angle has long been held to be low at high latitudes; the same perception has included the presence of darkness in winter, which has been related to the decrease of solar potential.

[125] Available at http://www.nordicenergy.org/.

[126] Latitude 63°25'N, longitude 10°23'E.

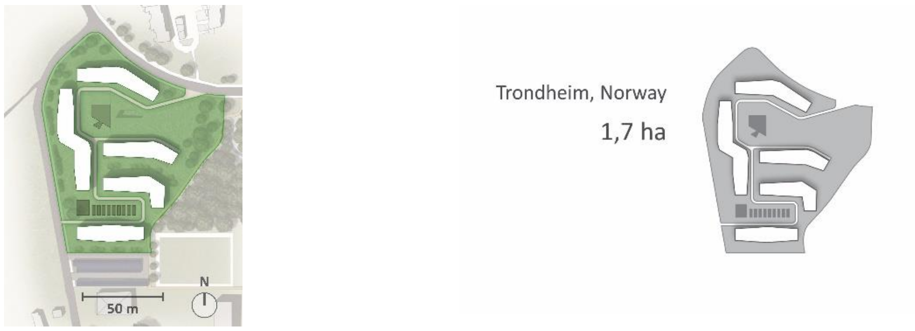


Fig. 93. Selection of the part of Øvre Rotvoll considered by the study (on the left), isolation of elementary features and quantification of site extent (on the right) (elaboration from Lobaccaro et al., 2016).

The parametric construction of this neighborhood starts following a pilot phase of documentary research upon local dwelling types, whose profiles would be optimized to increase as much as possible their solar accessibility on roofs. The vernacular unit proposed for such neighborhood reflects the volume demand of a Norwegian family and is known as the "*gable roof*": it has a 40% roof slope, two storeys with an interfloor of 3 meters, 8 meters long and 10 meters wide (Lobaccaro et al., 2016). Thus, floor area and volume amount to, respectively, 160 square meters and 560 cubic meters.

These measures depict a starting resident unit, which constitutes the basis for horizontal replication towards a row house system. Such replication is the result of a preliminary phase, where conventional and *additive* design predefines an attentive occupation in the horizontal sense. This phase, although non-parametric, lays out relevant constrictions to the following parameterization of form. First, spacing among row houses is not a random character: rather, it is set to guarantee solar accessibility to more than 30% of the South, East and West façades during summer period, i.e. March 21 to September 21[127]. Second, alignments of blocks are specifically studied to positively "frame" social spaces, acting as legible membranes for life and movement: in fact, rows follow a pattern distributed along the local access alley, which crosses the district from North to South, a public square with playgrounds for families, and urban gardens. Third, a decision is made for replicating resident units along three basic orientations, that is, three ways of establishing an interaction with the Sun: *1*) North-South, *2*) East-West, and *3*) rotated 30° to South-West from North-South axis (Lobaccaro et al., 2016).

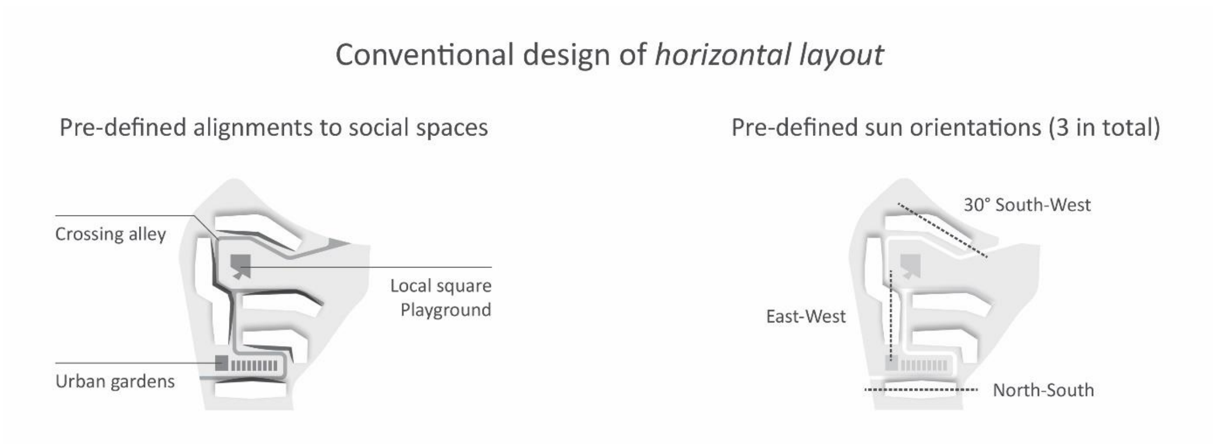


Fig. 94. The characters of horizontal layout emerging from a preliminary planning phase (source: author).

[127] An arrangement that is vowed to exploit as much as possible the maximal daylight period at Trondheim latitude, setting the base for successful strategies of passive and active solar systems.

The definition of *horizontal* occupation paves the way to the variation of *vertical* profiles of row houses, which takes place within the parametric environment. The section of starting resident units plays as a baseline profile for the "explosion" of sliding alterations, based, in turn, on three couples of input parameters. Each couple acts as the bundle of *X* and *Z* coordinates related to one roof vertex, thus the pool of parameters includes three input sliders for *X* coordinates and three for *Z* coordinates, one couple per one roof vertex. The three variable vertices of the section can move in compliance with domains fixed for slider components: lateral vertices have common ranges of no more than 4 meters (*X*) and 6 meters (*Z*), while the top vertex has a range set not to exceed central coordinates of lateral vertices.

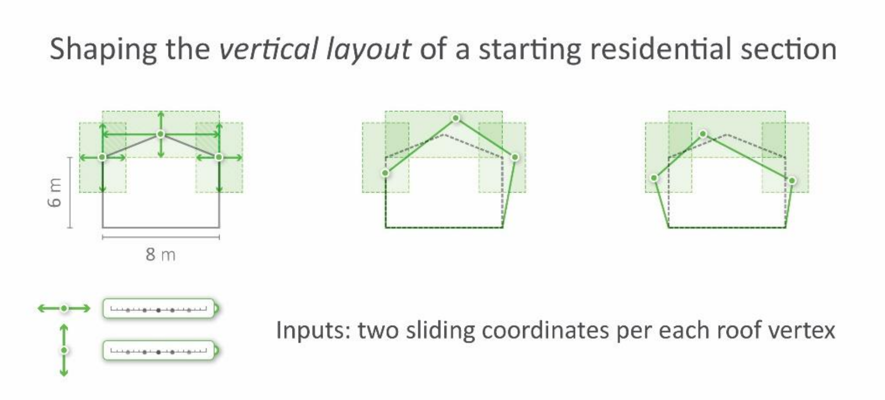


Fig. 95. Definition of input coordinates for abstracting the initial section (elaboration from Lobaccaro et al., 2016).

Once structured as a curve sensitive to parameters matched with roof vertices, the outline is first converted to a surface and then extruded along the *Y*-axis, so as to reproduce a width of 10 meters in accordance with site-specific typology measures. This central step, while providing the instructions that shall be propagated to final form, wraps a quite simple hierarchy for the parametric diagram, hinting that shape and volume of the extrusion would depend on the outline of the section, which, in turn, depends on coordinates set for its three roof vertices. This means that it is enough to handle three couples of parameters to govern much of the final envelop, with a particular influence on both size and slope of roof systems. This would happen preserving the original covered area and a width of 10 meters at the same time, due to the structure chosen for *associative* dependencies.

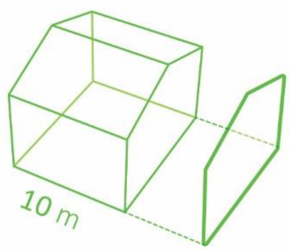


Fig. 96. Extruding the parameterized section up to 10 meters, so as to get a resident unit that would be responsive to the re-computation of roof coordinates (source: author).

The result of such basic assembly of *responsive* geometry represents a calculation basis for indicator measures, which would sensitively respond, in turn, to the parametric "swings" of each vertex coordinate. The researchers opt for three output indicators for assessing the energy performance of final form, moving toward a perspective of Net Zero Energy balance (Lobaccaro et al., 2016). The indicators are: *1*) *solar radiation* on roofs, calculated through *DIVA* plugin; *2*) envelop *compactness*; *3*) envelop *volume*.

Energy performance criteria	Indicator description and notes
Solar radiation level	Measuring the active potential of unit envelop, it describes the amount of irradiation (kWh) received per square meter of roof surface in one year. Estimating the irradiation level of roofs is a necessary step for calculating the room for installing photovoltaic panels from the morphogenetic root of the process. Both inclination and size of each roof surface drastically affect the indicator value. The irradiation level is calculated by means of *DIVA* plugin for Rhino and *Grasshopper*.
Index of compactness	The compactness index simply consists in the shape factor of the residential unit, given by the ratio of envelop surface to volume. Higher compactness corresponds to lower thermal losses through lateral walls, floor and roofs, which means better passive performance. Standards for this measure are taken from *Standard Norge*, a local private certification agency.
Volume of indoor space	The indoor volume of the residential unit is proportional to the amount of energy consumed for heating and cooling. In other words, it represents the demand to be balanced by means of envelop optimization.

Tab. 4. The three indicators chosen for appraising the energy performance of output units (Lobaccaro et al., 2016).

Through algorithmic definitions built in *Grasshopper*, it is now possible to evaluate every move of coordinates dynamically, interpreting the three indicators as performance criteria for outcome geometry. Yet, synchronizing the balance of energy measures toward the optimum implies conflating them into a meaningful expression, drawing from their single role as *bonus* or *malus* elements, to their overall, definitive payoff. A *fitness* function is set in this regard, so as to optimize such balance. Once the algorithm is provided with the three output shafts, the system is furtherly constrained to include a proportion of *solar radiation* on roofs to envelop *compactness*. Through the solver *Galapagos*, vertex coordinates become the *genome* of evolutionary optimization, while the ratio is chosen as a *fitness* to be maximized (Lobaccaro et al., 2016). Such definition is laden with clear logical sense, grounded on a simple mathematical property of quotients: maximizing that ratio would entail satisfying a goal of maximal radiation, while curtailing heat loss propensity as much as possible, based on envelop surface per unit of volume. Considering parametric settings as *genes* that shall be either kept or dumped in the struggle for survival[128], *Galapagos* performs as the "motor" of a closed loop that automates the interaction of genotypes with the adaptive capacity of phenotypes, sifting genes[129] against a condition of maximal fitness over and over again, until the best genes are finally found. Per each of the three orientations, the circuit is run until 80 to 120 cycles. Every cycle consists, in this case, of 50 alternative mutations, and takes the "best" previous generation, that is, the configuration of parameters giving the highest ratio between radiation and compactness, as a starting point for the following checks[130].

[128] In other terms, the struggle for determining the adaptation to optimal requisites better than other genes may ever do.

[129] Read "parametric values" for roof vertices.

[130] Once the process is stopped, output values of irradiation are crosschecked with the irradiation values cataloged on the web application of *PVGIS* for the same sun orientations (Lobaccaro et al., 2016). Although this step may sound punctilious, it serves as a useful option to verify *DIVA*'s automatism in terms of general accuracy.

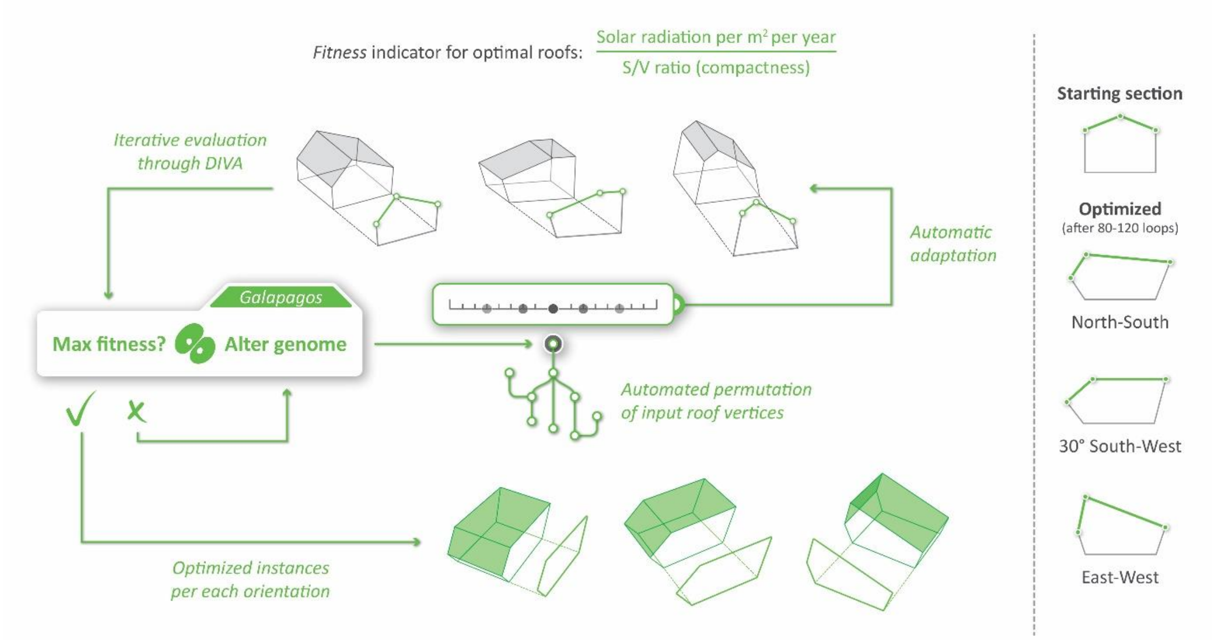


Fig. 97. Defining the *fitness* function for final envelops and schematizing the process of iterative search of coordinates able to maximize performance based on custom condition (on the left); the representation of sections resulting from the sifting process per each orientation (on the right) (source: author).

Once optimal units emerge *qua* finest compromise between radiation and compactness, the researchers choose to isolate, *bake*[131] and substitute corresponding sections to middle and turning points of starting blocks, based, of course, on their respective orientations. The final envelop system of row houses, after manual reinstatement, corresponds to a glowing "loft" from original to optimal solutions, found respectively at terminal and intermediate points.

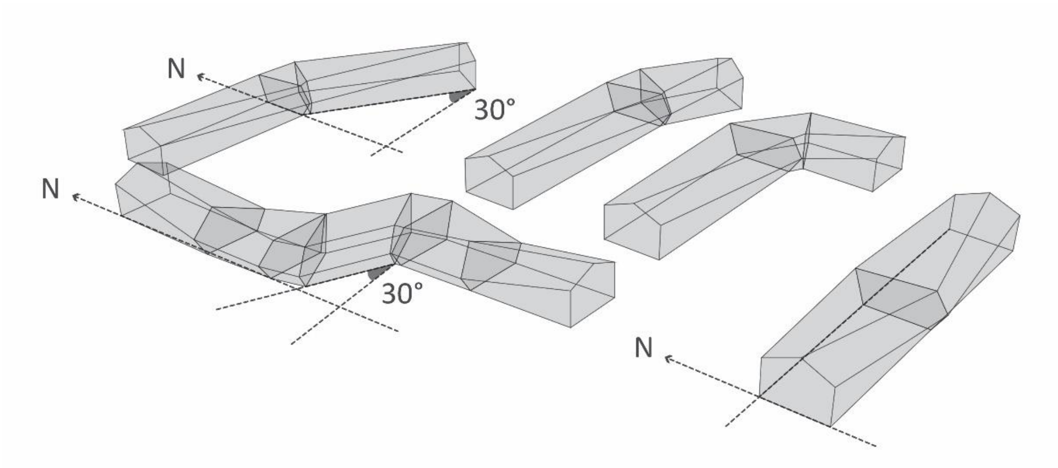


Fig. 98. Substituting starting sections with optimal ones at middle and turning points, according to respective orientations (elaboration from Lobaccaro et al., 2016).

[131] Which means, to transform *Grasshopper*'s "ghost" geometries into editable Rhino elements.

3.3.1. *Technology* – Leveraging the computational support in its *circular* option: grasping the chance for optimization of instances, using evaluation as a constant molding force

In this last case, we experience both parametric and algorithmic-computational support systems, leaving room for *linear* adjustments to parameters, but instead choosing to exploit a *looped* system as the solver of a heuristic optimization problem. Anyway, direct permutation of design instances is achieved through a *user-defined* matrix, just like in the previous case (*B*). The relative automation of geometric assembly neutralizes manual design inconsistencies, unless human element succumbs to error status situations within the algorithm and/or the lack of a meaningful translation of content between human intentionality and digital board vocabulary.
At least in relation to scope, this application totally walls the workflow within *Grasshopper*, with no need for external software during either or both data entry and evaluation phase: the process of shaping and re-shaping form incorporates energy feedbacks as in-built forces with an active "forging" role. This means not only simultaneous *responsiveness*, but a closed loop system between parametric settings and associated indicators. That is, *ad-hoc* constraints that translate measures pledged to the evaluation of form into *visual scripting* language. In this case, we find a measure of *compactness* or *shape factor* (surface-to-volume ratio) and, in parallel, incident *solar radiation* per square meter of morphological surface during a specified period at a precise latitude.
Here, the condition imposed to performance is also a compound one: solar radiation per square meter, or *energy density*, is confronted with the change in compactness of a starting residential unit at each vertex manipulation, by means of an additional constraint between the two output values. This custom *association* is represented by a simple division operator, available in *Grasshopper* as one of the elementary math components. We as humans confer a sense to such division beyond the mathematical meaning, since what we gain is not only an "aseptic" quotient, but a clever compromise between, on the one hand, the propensity to solar heat and thermal provision for future paneling, and, on the other hand, the propensity to heat loss through the S/V factor. In case *B*, on the contrary, we only observe distinct evaluations of shape factor and solar radiation, hinting that these are calculated as parallel outputs.

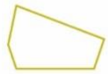
Algorithmic compliance imposes the unambiguous construction of inputs, and the same applies to constraints, which results in automatic redrawing of ghost geometries. The condition, other than being a custom expression of performance, supports an instant and unceasing *propagation* across transient instances along the optimizing loop. The process of optimization is designed to perform 80 to 120 loops, each with a different pool of random genes. In this respect, a feature that should not be taken for granted is the order of magnitude of timing, which usually reflects the number of involved parameters, their grain and extent, and the complexity of *fitness* function[132]. In this case, hypothetically, this could amount to a range between 30 minutes and 1 hour, which can be considered as good timing for the whole set of sun orientations[133].
The "sliding" opportunity here expands to a further accuracy of shape configuration, due to the concept of size and slope as inherently mathematical and continuous features. This also relates to the components used, which can bear and process *continuous* variables so that they project to output performance values, leading to detailed variation of energy indicators. In this new light, form undergo sharpening tension through higher detail, having computational power as the sole obstacle to the process, together with human (*mis*)understanding of algorithmic soundness and output meaning.

[132] Since time is always in short supply, this latter aspect may become decisive for the overall feasibility of methodology.
[133] These are, we repeat, South-North, East-West and 30° South-West (Lobaccaro et al., 2016).

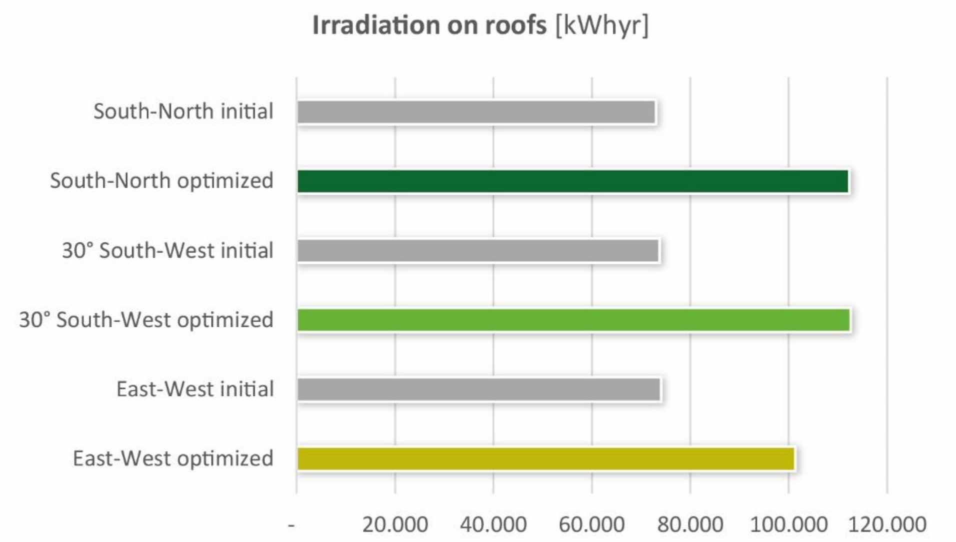
3.3.2. *Expendability* – Stretching the local typology within an integrated human-machine interaction, with the substantial increase of solar capture and the prospect of Zero Energy

The horizontal layout here is already defined through a preliminary, *additive*, yet complementary design phase. Interestingly, the typology sticks to a site-specific sensibility, despite the seemingly "universalistic" fashion of optimization concept. This third parametric experience does not work on ideal types anymore. We observe one typology, but this typology articulates different lengths and orientations within the same site, i.e. constraining the act of solving the compositional problem to different ways of harvesting solar potential, and thus achieving strong realism through complex setting compared to the other two cases. Despite the presence of only one type, it is not a simply isotropic aggregation: various orientations and spacing options mutually interact at once. The case shows the most appreciable distortion of typologies as a starting point for evaluation, though it is accomplished by means of conventional modeling. The highest level of realism seems to come about at the expense of a parameterization that is reduced to vertical layout only.
Aside from rethinking resident units from traditional criteria, the contextual sensibility should gild a meaningful interpretation of results with respect to a site-specific challenge. Parametric optimization takes into account local data, i.e. a compositional problem adapted to latitude and weather condition of Northern Norway. In this sense, the location is particularly interesting, as the case evaluates the opportunity to harvest sunlight as much as possible at Northern coordinates. Total volume per orientation depends on both local demands for residential units and the solar molding process[134].
Such predisposition process, after considering different orientations, insists on "tailoring" types themselves in their mutual spatial interaction. This aspect spurs from a realistic puzzle-box system of buildings, which denies "gridded" or stereometric arrays, belonging to pure imagination, to carve out solar-molded envelope configurations from their interactive play of obstruction. It follows that this application investigates detailed tuning of building envelopes as a way to use parametrics in the genuine definition of real design solutions and not anymore addressing suggestions coming from sample patterns.
In spite of this "surface chiseling", the results prove to be sharply eloquent, suggesting that parametric modeling could be a fertile technique even when coping with conventional design in a synergic perspective. This is clearly showed by a further countercheck of outcome forms: compared to starting blocks, optimal ones receive more than 50% more radiation for North-South and 30° South-West orientations, and more than 35% more in the East-West orientation (Lobaccaro et al., 2016). Note that the amount of irradiation scrutinized in this study only refers to the two roof surfaces of units, called *L* (*Left* roof) and *R* (*Right* roof) in the table below.
The absolute amount of radiation estimated for the roof areas of the district[135] is approximately 3.855.000 kWh per year.

[134] However, the system is constrained in such a way, that the X and Z domains imposed to vertex variations narrow down the room for output volume range.
[135] That is, not relativized to square meter of roof surface.

Concept	South-North		30° South-West		East-West	
	Initial	*Optimized*	*Initial*	*Optimized*	*Initial*	*Optimized*
Shape						
Compactness [m^2/m^3]	0,72	0,75	0,72	0,75	0,72	0,78
Volume [m^2]	560	554	560	558	560	495
Surface roof *L* [m^2]	43	95	43	84	43	91
Surface roof *R* [m^2]	43	30	43	35	43	35
Irradiation per m^2 on roof *L* [kWh/m^2yr]	640	828	675	884	866	843
Irradiation per m^2 on roof *R* [kWh/m^2yr]	1.059	1.132	1.047	1.095	849	703
Increment of solar potential [%]	**+54%**		**+52%**		**+37%**	
(Irradiation *L* + *R*)/ compactness [kWh/m]	**101.468**	**150.160**	**102.842**	**150.108**	**102.424**	**129.895**

Tab. 5. Comparative synthesis of optimization results (retrieved from Lobaccaro et al, 2016).



Gra. 11. Graph of solar radiation levels received by the roofs of initial and optimized units (elaboration from Lobaccaro et al., 2016).

The research also includes further examination of morpho-solar potential, exploring the room for actual energy production from an active viewpoint toward received irradiation. The hypothesis chosen for this study consists in high efficiency PV panels that, at the same time, would fit in the aesthetic concept of proposed architectures. In particular, the solar cells selected for this purpose have 22% efficiency (Lobaccaro et al., 2016). Other than solar radiation per square meter and solar cell efficiency, the estimation also requires the percentage of useful PV cell area. To do so, a sample of four different panel sizes is selected. The comparison of panel area

and cell area per each sample determines an average around 80% to be applied in the calculation of energy production.
Once collected essential values, the total energy that can be produced on site amounts to 146 kWh/m^2/year, on condition that an appropriate PV technology is used (Lobaccaro et al., 2016). Operational energy consumption, depending on output volume, could reach 75 kWh/m^2 for the whole neighborhood. This depicts a particularly promising scenario, where the amount of (renewable) energy supply would cover nearly twice the operational energy demand of the entire building complex (Lobaccaro et al., 2016).

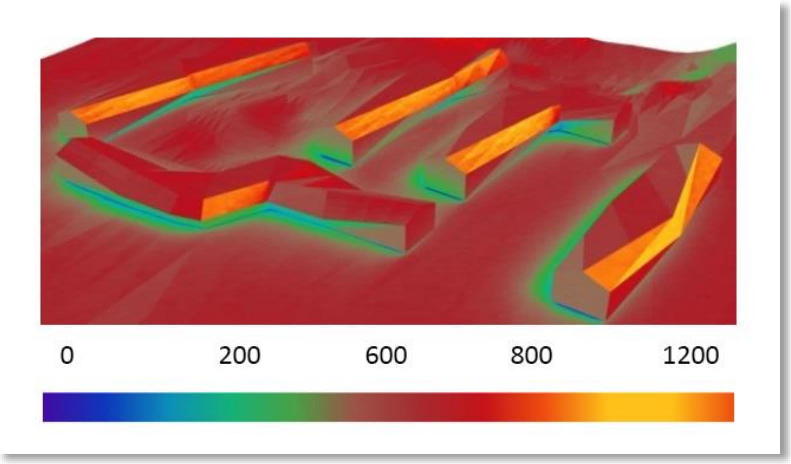


Fig. 99. Solar radiation map of the optimized scenario (retrieved from Lobaccaro et al., 2016).

Aside from absolute results, the parametric optimization of envelops can also be credited with prompting form to achieve a degree of relative energy balance, here estimated in terms of equivalent carbon emissions: i.e. CO_2 spurring from energy consumption and materials, versus CO_2 comparable to the total energy produced on site. Equalizing the two measures would determine the *ZEB* goal of the project.
In this regard, researchers choose to convert both values from kWh to equivalent CO_2 using the *ZEB* factor for energy in Norway, which amounts to 0.132 kgCO_2eq. Results show a valuable payoff that portrays the accomplishment of a zero emission neighborhood: the CO_2 emissions from materials and consumption render 19.20 kgCO_2eq/m^{2}y, while energy production corresponds to a proportionate rate of 19.35 kgCO_2eq/m^{2}y (Lobaccaro et al., 2016).

Fig. 100. Rendering of the project (retrieved from Lobaccaro et al., 2016).

3.3.3. *Complexity* – Safeguarding a site-specific awareness with preliminary designs of solid-void relationships, but leaving optimization to building envelope refinements

Even with reference to complexity, this third study differs a lot from the previous two. What we clearly notice is that the application assumes architectural detail to be the main concern, stopping at the refinement of envelops. In other terms, we lack a parameterization of solid-void schemes that, on the contrary, would match energy outcomes with “unlocked” or “sliding” occupations, governing space from a *full* urban design perspective.

Nevertheless, we can even draw inspiration from distortion factors that appear to come from real context pressures, going beyond the mere energy capture: the most evident is the definition of social spaces of connection, which crosscuts energy evaluation and *form-finding*. However, these nuances of design belong to preliminary, non-parametric phases, as they do not travel with the energy dimension along the same parametric grids; rather, they stand for a static and upper-level constraint system that only leads to an architectural refinement of forms, without really expanding the urban design dimension through different alternatives of block assembly. Both spacing and orientations are pre-defined through a conventional modeling phase and cannot be altered as *associative* elements of design. These factors are well grounded on solar criteria: deviations from North-South axes only include South-facing rotations, while mutual distances guarantee a minimum threshold of solar accessibility during summer period, thus contrasting indiscriminate applications of solar angles. But there is more to it. Distances also respond to site-specific requirements for open space from both quantitative and qualitative viewpoints, thus injecting overarching factors of distortion into the system. As these are real-world definitions, such proportions bring about higher realism, but still we cannot *abstract* them for any true parametric variation, in terms of neither size nor distribution.

The optimization process, though affecting envelop phenotypes with fairly visible results, insists on pre-packed suggestions, not on algorithmically embedded urban design arrangements. Horizontal design and density levels of row house systems, aside from minor modifications at section level, cannot undergo any “glowing” process of *associative* molding.

3.4. Drawing from parametric experiences to devise more realistic occupation measures: opportunities and frictions of increasing complexity toward the urban design realm

Learning from selected parametric practices, based on interpretative layers

The three case studies exemplify three different strategies for predisposing forms to efficiency in terms of solar performance within a framework of density pressures, efficiency that we can find in morphological re-arrangements of the built environment at the neighborhood level. It is important to note that the first two cases expect designers to treasure compositional suggestions that come from explorations of sample patterns, depicting an indirect predisposition, while the last one prompts actual forms directly, but with significant restrictions. Our integration would restore an intermediate step: this attempt points to shelve overly simplified patterns through concepts we find in practice, such as parceling and coalescence of buildings, while still preserving the parametric abstraction of block assembly.

In this new light, we might consider our model as an inventive, though partial inspiration for two development routes. On the one hand, we could opt for experimenting the model as a pattern generator, deducing guidelines for factual design based on relatively higher realism of sample occupations. On the other, we could interpret it as a starting "stone" toward a parametric urban design environment; as we imagine that technical frictions of tools might be solved for scales larger than architectural and engineering domains, we could expect incremental sophistications toward a more concrete support to real masterplans. In this perspective, parametric control could aspire to be protagonist in molding dense, energy-savvy and quality-oriented forms from the early design stage (Steinø & Veirum, 2005). Through this prototype, we hope to capture at least the flavor or what we could see in future urban design practice.

The properties of our parametric instrument descend from reflections emerging from the three layers used for interpreting these studies[136]: **1**) *Technology*, **2**) *Expendability* and **3**) *Complexity*.

1. *The Technology layer of interpretation* – Through this first lens, we have considered the degree of computational and algorithmic support during the "budding" process that links *abstract* matrix to the generation of *concrete* instances, filtering the ease in obtaining results. We could distinguish three intensity grades.
   The first grade consists in no computational support (case *A*). In this case, we could notice at least the conceptual essence of abstraction through a "recipe" for combining mutable options of input. However, management limits of the human element led to a coarse resolution of data from the standpoint of both parameters and evaluative results. Besides, the exploration of discrete options, forms (18 models) and values amounts to scarce workflow integration, splitting the process into three different environments (*Excel*, *CAD* and *PPF*), and separating evaluation moments from the rule system informing geometry.
   The second grade represents a considerable step forward in terms of process integration, consisting in an algorithm based on *linear generativity* (case *B*). The involvement of a genuine algorithmic support helped achieve much higher resolution with respect to input data. This, joint with the specification of unambiguous rules, sped up the whole process of instance generation per every input, spawning wider amount of models (60 vs. 18 of the previous case), the latter being all consistent with conditions, and thus part of a *continuous* gradient. Continuity is a property denoting the overall mechanism as a whole: process "gestation" took place entirely in *Grasshopper*, with no need for external platforms, supporting the connection of instances to real-time evaluation within a common constraint system, based on custom definition of indicators (formal measures) and a specialized plugin, *GECO*, which performs energy

[136] Layers that are far from being standalone views; rather, we appreciate their contents for being expressions of connected and intercommunicating features.

appraisal in connection with Autodesk *Ecotect*. As we already noticed, the algorithm has been designed as an "undeviating" process from input levers to evaluative components: the former could be humanly controlled; the latter could compute results once at every change of parameters, portraying a *fine-tuning* or *forward design* paradigm.
The third grade is a further sophistication of algorithmic modeling that supports a closed optimization loop or, in other words, *circular generativity* (case *C*). This is the highest level of support to the generation of self-consistent, *associative* models, where the algorithm is a digital process encompassing form and evaluation with top dynamism. By propagation, the continuous range of input data is mirrored by the transient nature of output models. The detail of informers here showed particularly high resolution thanks to the use of unambiguous "coordinates" of occupation, something evidently legible for further operations on geometry. This condition led to a virtually endless number of possible permutations for coordinates, each corresponding to one instance model out of the generative matrix. As with the previous case, *Grasshopper* has shown the opportunity to incubate and integrate both genetic formulation and evaluation of models within the same workflow, this time thanks to the energy solver *DIVA*. However, this also paved the way to an augmented degree of integration. In fact, the system has been constrained to reproduce recursive appraisal thanks to *Galapagos*, the evolutionary solver for *Grasshopper*. *Galapagos* unlocked an *optimization* or *inverse design* paradigm, taking over parametric coordinates to find their optimal configuration, grounding the search on continuous feedbacks from a custom fitness expression and depicting a self-fueled trial-and-error cycle of iterations, back and forth from outcome values to input data and *vice versa*.
The three cases highlight the importance of algorithmic programming to the relative success of parametric modeling, each in its own way: the first one suffers from the actual difficulty in reproducing a "solution space" manually; the other two represent gradual levels of algorithmic integration and a proportionate extent of this space. Both utilize *Grasshopper* for reconstructing the "genetic code" of morphology, so as to evaluate it in all the possible appearances that might emerge from that code, speeding up the formulation of models at the same time. *Grasshopper* is commonly credited with being the most competitive modeler for parametric design when it comes to the management of complex or multifaceted forms. It empowers human-machine interaction through visual vocabulary, and the handiness of online communities happens to be larger and expanding; besides, *customization* of performance criteria represents a fertile ground for further development of design dimensions and purposes, leading to the integration of special components for joining form with sophisticated and *ad-hoc* measures. These characters of computational support suggest that our new model could further put *Grasshopper* to the test, mating the power of procedural geometry with custom measures and specialized plugins for evaluation. Specifically, the application would use a compound *fitness* as the "eye" of a purposeful *optimization* cycle, but also as a way to experiment heuristic search of solutions through *Galapagos*, drawing inspiration from the experience of case *C*. This process would insist on energy measures. However, the inoculation of additional measures of morphometry would also call for calibrating outcomes of energy optimization in respect to implications for other profiles of performance. This latter opportunity draws inspiration from case *B*, adjusting parameters incrementally to balance the impacts of design choice in real-time through a *fine-tuning* practice.

2. *The Expendability layer of interpretation* – Through the second lens, we have valued the contribution of parametric studies to urban design, unveiling the "freedom" in relating density loads to options for casting shapes, describing the role of such freedom in formulating implications for solar performance, and, thus, filtering the usefulness of results. The study of shape-density interactions and their impacts in terms of energy capture helped appreciate the applications in terms of type of strategy, informative value of results and applicative prospects for urban composition.

Case *A*, though alien to *associative* dynamics, proved to guarantee the *independence* of density dimensions and shape structures, at least at conceptual levels. This character has been anything but banal for morpho-energetic design, because it gave the flavor of how polarizing input can release extensive combinatorial opportunities, and equally extensive energy implications. Such "freedom" in combining aspects of form, other than having somehow limited resolution, stopped at pattern recognition, but was in line with a strategy that is actually feasible in design practice. Indeed, we handle coverage separately from plot ratio, as well as horizontal and vertical distribution of, respectively, spacing and heights. This amplified the solution space, balancing, in a way, the reduction of input we observed from a *Technology* perspective. With respect to the three measures selected for appraising models, namely openness, daylighting and solar radiation, the overall picture of efficiency drew interesting benefits from combinational freedom, making it possible to densify space inoffensively for exposure. Something recalling the concept of *Pareto-efficient* allocation, this time in relation to the environmental quality of built environments. Such behavior has been conceivable only through the multiplication of design alternatives, which led to strategic scenarios for high-density solar cities. For this reason, we will consider preserving the unambiguous separation of shape, density and coverage as a good advice for our model.
Case *B* widened the scope of reflections, interpreting shape and density relationships from a different perspective. Polarizing the two elements of composition implied detaching not morphology *per se*, but, more properly, its intimate process of generation from energy impacts. Here, the rule of thumb represented a chief element of connection, merging shapes, densities and conditions for solar access within a co-genetic mechanism that made them connatural. We could not reshape the dissemination of bulks but with floor number, which, by the way, did not even distinguish density from shape anymore: adding floors only meant increasing vertical occupation, with lopsided effects on both dimensions. In turn, these depended on the ideal type involved in the process. Solar-induced behaviors acted according to typology and floor number; as such, they played a central role in permeating the generative adaptation of form to change. Intersecting input choice with the automatism of a rule of thumb helped submitting different styles of occupation to the scrutiny of "pure performance": this constraint has been a worthy stratagem for equalizing models on a comparable level, but shrank a lot our room for governing pattern formulation in complete autonomy.
Case *C* took this co-genetic foundation of procedure to extremes, while surging, at the same time, from a sound control of occupation. This is at least the perception we get from the process as a whole; however, the control seen in terms of block structure and open space system fell entirely into pre-parametric definitions. In effect, parametrics have been resized only to a machine-based, *associative* integration for an inherently human-based, *additive* project, restraining the scope to envelop details, but not without generous results. Working on envelops parametrically served as a strategy to complement the concept of occupation with decimal precision, this time considering the approach as protagonist of a genuine delineation of real geometries and not exclusively as a tool for studying generic patterns made up of ideal types. The choice of using vertex coordinates as input levers conducted to an intuitive understanding of the solution space, boasting simplicity, and yet granting huge information on energy concerns. It was sufficient to handle roof vertices to produce wide-ranging alterations of envelop geometry, with substantial impacts on properties that are crucial for harvesting solar energy. These were first of all both size and slope of rooftops. In parallel, changing roof structures implied parallel and equally relevant effects on both volume and compactness of resident units, which, together with radiation levels, would have been central to a condition of energy balance. The co-genetic principle of envelops lay on embedding this complex condition in the process of generation, loading geometry with a congenital "talent" that came from quivering and mutual interactions of energy poles. This inward capacity found its barycentric point in the *fitness* function. In fact, the *fitness* has been constructed in a quite ingenious way, making the three impacts (volume, compactness and radiation) converge to a precise equilibrium. Equilibrium where the increase of inbound energy and volume supply would have met the decrease of

outbound consumption. Despite granting undeniable results for environmental quality, the approach gave disproportionate centrality to automation, assigning machine an active role in casting final forms, but leaving the designer with a passive certification of aftermaths. Clearly, the human element was not marginal at all in respect to parametric-algorithmic definitions; however, much of the control of shape and density aspects fell into conventional modeling. As the fitness happens to be in line with our conceptualization of efficient occupation, we will transpose the same formula to simulate at least the propensity to both density and energy equilibria, this time ensuring a certain degree of autonomy in manipulating shapes as separate from the determination of densities.

3. *The Complexity level of interpretation* – Through the third lens, we have examined the influential bundle between built (solids) and open spaces (voids) across the three applications, with reference to the importance of *user-defined* constraints as determinants. These aspects are strictly connected to realism of outcome geometries, because detailing input and ruleset calibrates the closeness of virtual morphologies to real-world patterns, moving from the *generic quality* of simplified environments to the *specific quality* of urban spaces, and filtering the representativeness of results. These spaces respond to multiple pressures and not exclusively to solar design. The purpose to achieve a relational quality between built and open spaces is what can provide realism to generative simulation, because it constitutes the essence of compositional dilemmas. As such, it may inject those "distortion factors" that, forcing meaningful occupation of space, contrast the aim at capturing as much density and energy as possible with down-to-earth, complex equilibria of urban design activity.
   Drawing from what the three cases have taught us in terms of *Complexity*, we may consider devising a parameterization of horizontal and vertical profiles that could unleash some leeway in occupying space while still granting a certain level of intuitiveness for human elements. In this framework of mind, the choice of variation and correlation systems would point to *abstract* occupation as much as possible to determine "glowing" transfigurations of form. This new perspective would attempt at supporting the *specific quality* of design, interpreting isotropic distributions of units as one possible arrangement out of many.
   This implies that types and spacing can be varied liberally, which would help define (de)concentrations of units with precise parametric control. With respect to case *A*, the new model would dump the indeterminacy of randomness; with respect to case *B*, it would embrace alternative distributions of solid-void structure; with respect to case *C*, it would "unfreeze" preliminary delineations of open space and built backgrounds. Diverse occupations may co-exist in their mutual interaction, depicting composite arrays that would be open to mixtures of regular and irregular schemes from both the horizontal and vertical viewpoint.
   The new model would express specific quality even through a more flexible permutation of typologies. In truth, occupation would be parameterized to a point where speaking of "typologies" might become inaccurate. Rather, types would be notable instances out of several middle "photograms", and occupation of space would "slide" along the site, unblocking *continuous* gradients of solutions per each building unit. This should overcome the limits linked to the use of single types per pattern, where all buildings shared static footprints (typical of both case *A* and *B*), and the burden of pre-packed boundaries, defined through conventional modeling (characterizing case *C*).
   The room for manipulation of units includes properties that could approach real-world structures even more. Specifically, other than mating different types within the same pattern, we refer to opportunities for adapting units to deformations of site geometry, culling solids in favor of voids though keeping the total volume, and conglomerating more than one unit into some sort of combinatorial massing. Case *A* was totally alien to all of these properties. Case *B* implied deformed units based on circular development pattern, culled solids only according to a rule of thumb, with no preservation of volume, and did

not consider at all the cross-combination of different geometries. Case *C* strictly put away these opportunities for the sake of a minor redefinition of envelops.

This is more or less the prospect for horizontal occupation, which mainly insists on definition of footprint and spatial dislocation. Vertically, heights would differ at the scale of individual units, based on continuous gradients as well. These would depend on volume load and horizontal size. Such definition, though being partially constrained by coverage, would unleash the intermediate domain between uniform and varying heights (unlike case *A*), differentiate the same instance pattern with mutable skylines (unlike case *B*), and "shelve" architectural refinements on account of more substantial (urban) effects (unlike case *C*).

Together with the other dimensions of complexity, orientations helped inspiring a further accomplishment. In this case, our definition happens to be somehow perfectible, but still, it may smooth the path for additional sophistication. The new model enables a parametric rotation of development site, based on the range of a perigon. This allows for molding the same pattern against all the possible orientations it may assume, which is something more than considering fixed (case *A*) or conflating angles (case *B*), but still less than parameterizing rotations of single units (i.e. less than abstracting orientations found in case *C*).

Distortions are probably the central feeders of specific quality in our integrative matrix. Specifically, what we intend for "distortion factor" is a manifested need to pledge the production of urban space to characters that may stimulate a complex equilibrium with energy performance. Joint with a goal of densification and solar capture, these characters would constitute the typical "forces" that, based on the multi-purpose perspective of urban design, invoke precise schemes of occupation, introducing some degree of *specific quality* into urban patterns. Within this framework, such precision in the organization of obstructions becomes a necessary requisite when it comes to define inputs for the parametric system, not only because we imagine probing high-resolution gradients of form, but also because we require variations to give a sense to extra forces, which of course would have their own tolerance intervals and intensity scales. Precision would become, in this light, a stratagem for equalizing the "legibility" of occupation change from the standpoint of more than one factor.

In particular, our model would draw distortion from occupation schemes that we commonly assume as design tactics devoted to making a *place* out of an urban space, something that pushes morphology to acquire profiles supposed to encourage perceptive features, social encounter/control and experiential appeal for human beings (Thomas, 2016; cf. Jacobs, 1961; cf. Bentley, 1985). Notice that these profiles of occupation only stand for morphological predisposition to frame places, which can be an influential strategy, but not a deterministic guarantee of a socially safe, attractive and vibrant environment: all effects that go beyond the "*morphological dimension*" of urban design (Carmona, 2010), toward political, administrative, economic and cultural efforts (Friedmann, 2010). In one word, the morpho-social variables we would use to evaluate such predisposition are nothing more than *proxies*, which, by the way, amount to a very limited number[137].

[137] As a matter of fact, we will consider in a few lines three variables juxtaposed to energy indicators: one for horizontal occupation, one for vertical occupation and one for both horizontal and vertical occupation.

It is interesting to note how sensitive the perception of a complex morphology, such as the ones describing an urban environment, proves to be even when simple variations of geometries have a role in the permutation of design schemes. Steinø (2010) proposes an example of such degree of flexibility by investigating the chance of combining geometric and parametric thinking, in order to bypass hard scripting sessions with a considerably accessible approach to parametric urbanism for every level of expertise.

The example probes the combinatory flavor of this relationship with reference to the same building potential, something very similar to compositional studies in which different urban configurations arise from fixed densities, with just as many different urban effects (cf. Falco, 1999; Gabellini, 2001). Mirroring the complexity of urban design as a discipline (Carmona, 2010), these urban effects may involve diverse and potentially conflicting matters, such as visual *stimuli*, shadow densities, green layouts, ventilation or space control patterns, both private and public.

In this example, we consider the ordered telescoping of an urban structure, which traces the linear hierarchies of a *propagation-based* algorithmic structure. Each building bulk occupies a land plot, while a group of land plots forms an urban block where all objects are confined within an orthogonal layout. The example aims at illustrating how, by way of a conscious application of simple knowledge of geometry and symmetry, we can generate radically different solutions through elementary steps. In this case, the author manipulates features like building shapes, orientations and alignments by basic tactics of reflection, shift and rotation in steps of 90 degrees. By applying 2D rotation and reflection within the confines of orthogonality, the land plot shows to yield eight different orientations.

Setting up a new layer of dependency leads to the amplification of combinatorial alternatives. In particular, the example considers adding a building to the plot in a way that both of their front corners are overlapped. This operation equally allows for eight orientations of the building bulk on its land plot of reference. From now on, we assist to an exponential increase in the number of geometric combinations as we pass through the cascade of our hierarchical layers: the eight building orientations for each plot orientation result in sixty-four unique instances of building-plot orientations in space. As shown below with the two resulting environments, users can generate quite different situations simply by combining (a variable number of) these sixty-four different configurations (*figs.* 112 and 113).

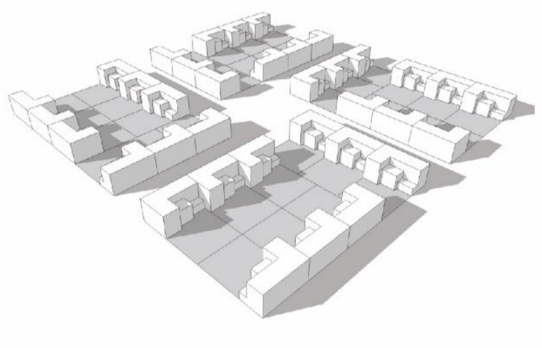


Fig. 101. Identical urban blocks composed through identical plots with identical building bulks (Steinø, 2010).

Fig. 102. Identical urban blocks composed from 4 differing types of plots with identical building bulks (ibid.).

In this shift from *fig.* X to *fig.* Y, each urban block keeps the same building bulks, which means that density is an invariant aspect. Moreover, every block shows three instances of plot type **a**, the one with buildings colored in green, which are unchanged from *fig.* X as well. The remaining plots vary from *fig.* X (plot type **a**) through rotations of 180 degrees (type **b**), 90 degrees (type **c**) and -90 degrees (type **d**) respectively of the building bulk to the land plot.

Interestingly, building bulks are all congruent in both images. Let us notice that each has a uniform and a rough side, and the two sides can be placed across as well as along the length of their plot. A simple rotation of the six possible instances of one identical bulk in relation to the respective plot results in either a very regular or a very irregular morphology of the overall urban space (Steinø, 2010), with direct and indirect implications in terms of visual, social and environmental quality of public and private space. The perception of internal and external life from the point of view of residents is a rather sensitive matter that becomes of primary importance when we come to design *places* of urban experience more than mere *spaces* of dimensional choices (Carmona, 2010). With this respect, we could reason upon formal elements like the fractal dimension of frontages, the entropy of façades and visual *stimuli* (Osmond, 2005), the relationship with the public space of the street, but also the levels of visual and physical accessibility to private entrances, which mirror the sense of security for inhabitants (Porta & Renne, 2005).

The unambiguous relationships among the hierarchical layers of this simplified environment lead to the easy generation of radically different scenarios of urban transformation, with relatively low effort if we think that the two hypotheses above diverge with only few steps of rotating and mirroring either the building on the plot or the plot on the block (Steinø, 2010). It should be noted, of course, that whether one scenario is preferable to another is strictly a *value judgement*, which is beyond the scope of technical modelling by parametric means.

Since the model is made up of combinatorial *strata*, changing the parameters for each *stratus* will reflect for its set of instances. This is a core characteristic of a parametric system, which traces back to what we have noticed in the very structure of algorithmic diagrams. Each layers of the design is bindingly nested inside the others in a cascade-like system of interdependencies. *De facto*, a few changes may lead to draconian effects across the model as a whole, in adherence to the *propagation-based* nature of the diagram. Urban structure becomes a clear set of hierarchies and dependency regimes that can be tested and finalized to a specific performance through the manipulation of inputs and the interpretation of outputs[138].

It is not hard to see the potential of this approach, however simple it may seem, when going beyond the very simple, but limited example described by Steinø (2010). In truth, users can achieve virtually innumerable geometric variations by introducing, for instance, non-orthogonal forms, rotations and scaling techniques, whose product would consist in ever more complex variations of building, plot and block configurations. Besides, the introduction of non-geometric parameters such as materials and colors, or other types of parameters such as vegetation and street layout indexes (Morello, 2010) would expand the spectrum of formal manipulation even more.

Of course, important discussions about the quality of urban space during *design synthesis* often involve a number of different stakeholders. In this sense, we cannot devolve decisive decision-making responsibilities to the sole computer-based part of the job, for urban design represents social and cultural processes leading to (hopefully) shared products (Palermo & Ponzini, 2014). However, before reaching phases of architectural detailing, bulk issues such as morphology, density and design variations call for an easy way to test different scenarios in order to foster interdisciplinary evaluation. To this end, the approach illustrated by Steinø (2010) is simple yet powerful.

[138] In the given example, the building bulk forms the lowest level in the multi-layered hierarchy. The building bulk layer is nested inside a plot layer subsumed by the urban block, which, in turn, is nested inside a site. Hierarchizing the parceling system at a level higher than the one of building bulks may be a decisive move for consistent changes in the distribution, alignment and orientation of building structures throughout the transformation site.

With respect to Steinø's model, we agree about the total neglect of density as a parametric dimension, in favor of pure transmutation of shapes. The interest is legitimate, but we cannot ignore that exploding shapes across degrees of density is central to designing high quality environments whilst minimizing resource consumption in terms of energy and land. This pushes us to fully embrace both dimensions parametrically, so as to appreciate their room for convergence. The control of space through parameters of occupation would adjust forms to return a correlation between quality and density (English Partnerships, 2000). The interpretation we found in Steinø (2010) suggests nothing in terms of density, but concentrates very clearly on the relevance of well-organized solid-void systems and on how much these systems are sensitive to change in occupation. In particular, among the reflections emerging from our commentary to Steinø (2010), we appreciate the control of public street space, the perception of entropy and the relationship between indoor and outdoor space, which led us to imagine three concepts of distortion linked respectively to these features. The first is a horizontal one, the second is a vertical one and the third is a both horizontal and vertical one.

In short, what we intend to recreate is not (only) a quantitative exploitation of space based on aseptic, unrealistic and mono-parametric conditions of efficiency, like mere solar capture and obstruction angles, but a qualitative interaction among geometries reacting (also) to pressing demands of occupation. These would represent the expression of a multi-parametric dimension, asking for a cautious compromise between densification, energy aspects and formal qualities, in line with the inherently complex equilibria of urban space design. In other terms, we would like to grapple with a model where the (precise) choice of occupation also considers distortion forces for energy performance, getting closer to a more realistic approach.

Our model is, of course, nothing but a very rudimental application of parametrics to the formulation of urban patterns, an application where options of occupation, while providing higher precision compared to case studies, still meet relevant boundaries. Besides, distortion factors, which are represented, in turn, by formal quality measures, are poor in number; as such, they simply cannot cover the whole set of conceivable design demands. Indeed, this is just a little exercise that performs not as a "complete" device, but as a humbler starting point for future refinements, which would not precede, but adapt to the incremental steps of complexity ladder. By now, it can serve as matter for reflection upon the inertial elements of methodology we could find in respect to our increase of complexity, gaining the awareness that the ability to manage forms and their problems of efficiency, while granting real-time knowledge and *self-reflexive* feedbacks on design impacts, may spot substantial obstacles from the procedural perspective of parametrics[139].

[139] This hints that wider liberties in formulating obstructions results in higher responsibility for technical and management duties, which always stay on behalf of human elements.

3.4.1. A starting point of complexification: defining an algorithmic matrix for connecting parametric occupation of a block with solar gain and lateral factors of quality

Similar to the example hypothesis we have seen in Steinø (2010), the process of assembly has been organized as a hierarchical explosion of layers that comprised delimitation of development, parceling, superimposition of building bulks and determination of heights per generated unit. In other terms, we have considered starting from something that we generally find in urban design practice.
These represent operations that are so frequently used by practitioners that can be encoded into modular and reusable algorithmic subsets. The literature calls them "*design patterns*", which are credited with sharing a considerably high level of abstraction and common meaning (Beirão et al., 2012; Gamma et al., 1995; Woodbury, 2010).

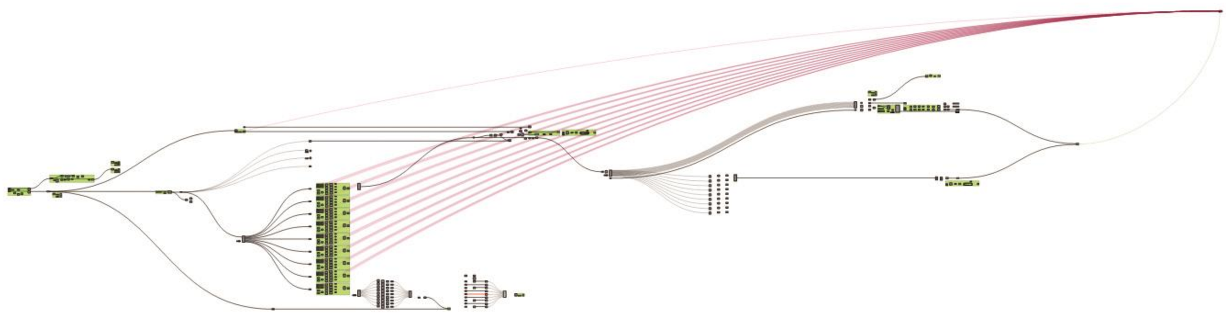


Fig. 103. Zoomed-out view of the algorithmic diagram built in *Grasshopper*, giving at least a clue of the entity of constraint system required for our condition; subsets of this matrix will be discussed separately through series of zoomed-in excerpts (source: author).

List of input data	List of output data
Eight Rhino curves for surrounding plots (*stored*)	Volume geometries of surrounding blocks
One Rhino curve for the tester plot (*stored*)	Volume geometries of units of the tester block
Angle of orientation in degrees (*slider*)	*Compactness* of tester units and block average
Number of plot parcels for tester plot (*slider*)	*Solar energy density* of tester units and block average
Volume ratio for surrounding blocks (*slider*)	*Fitness* ratio (mean *solar density* over mean *compactness*)
Volume ratio for tester block (*slider*)	*Natural surveillance* of tester units and block
X and *Y* coordinates of horizontal occupation (*sliders*)	*Height diversity* (variation coefficient of building heights)
Grid resolution for energy analysis (*slider*)	*Spaciousness* of the tester block
Period of time for energy analysis (*slider*)	3D previews for *compactness*, heights, *surveillance* levels

Tab. 6. Synthesis of what the whole solver required (input information) and produced (output information) (source: author).

Through container components, we considered importing a set of Rhino curves into *Grasshopper*'s canvas. The virtual environment consists of a rather uniform array of urban blocks, in terms of both size and density range (5 to 10 m^3/m^2), so as to reduce the edge effects for solar evaluation while warding off distortion of results. The central curve in *figure* X represents the perimeter of a development site where forms would come to light as "molded" by selected efficiency criteria in real-time, based on options of spatial occupation. As a hierarchically higher condition, we incorporate the parametrization of exposure angle for future and more refined tests. The whole environment is sensitive to angle of orientation (0-360 degrees) and heights of surroundings, which come from the intersection between a building width of 15 meters and a plot ratio of 7,5 m^3/m^2 (within a range of 5 to 10 m^3/m^2; just as for the tester block – see *figure* X).

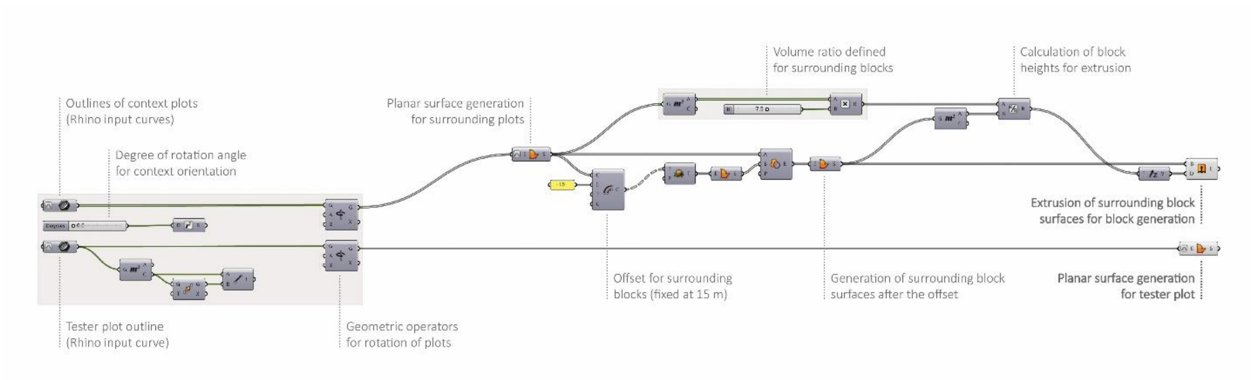


Fig. 104. The sub-matrix assembled at the beginning of the solver for generating both fictitious context and plot surface of our parametric development (source: author).

List of input data	List of output data
Eight Rhino curves for surrounding plots (*stored*)	Volume geometries of surrounding blocks
One Rhino curve for the tester plot (*stored*)	Surface geometry of the tester plot
Angle of orientation in degrees (*slider*)	
Volume ratio for surrounding blocks (*slider*)	

Tab. 7. Synthesis of what the subset required (input information) and produced (output information) for context generation and orientation (source: author).

Fig. 105. Selection of the surface geometry generated for the tester plot and indication of measures (on the left); view of the context and hypothetical rotations. We chose to bind the experiment to the original N-S orientation (0°) (source: author).

With the help of the open source plugin *Lunchbox*[140], the process proposes to constrain the generation of buildings to a parceling system, which imitates a typical design practice. Pictures in *fig.* X represent diverse subdivision options, but with an equal degree of volume ratio. The matrix has been organized to guarantee a maximum of nine parcels, due to a basic management purpose: in fact, the *specific quality* of occupation, which assumed the chance to assign a different form to every bulk[141], required making manual replicas of subset definitions to develop likewise different built areas out of each parcel.

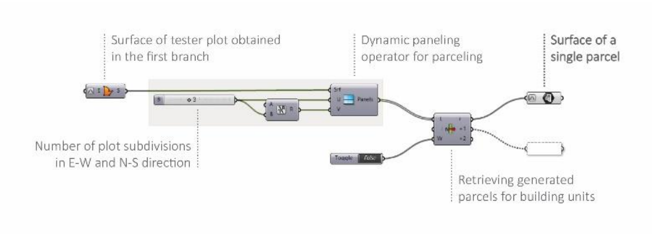


Fig. 106. The sub-matrix assembled for subdividing the tester plot surface into a pattern of parcels. The pattern supported by this definition is exclusively regular, meaning that each parcel is simply a submultiple of the plot (source: author).

List of input data	List of output data
Surface geometry of the tester plot (*stored*) Number of plot parcels for tester plot (*slider*)	Surface geometries of single parcels of the tester plot

Tab. 8. Synthesis of what the subset required (input information) and produced (output information) for parceling as the ground of urban massing operations (source: author).

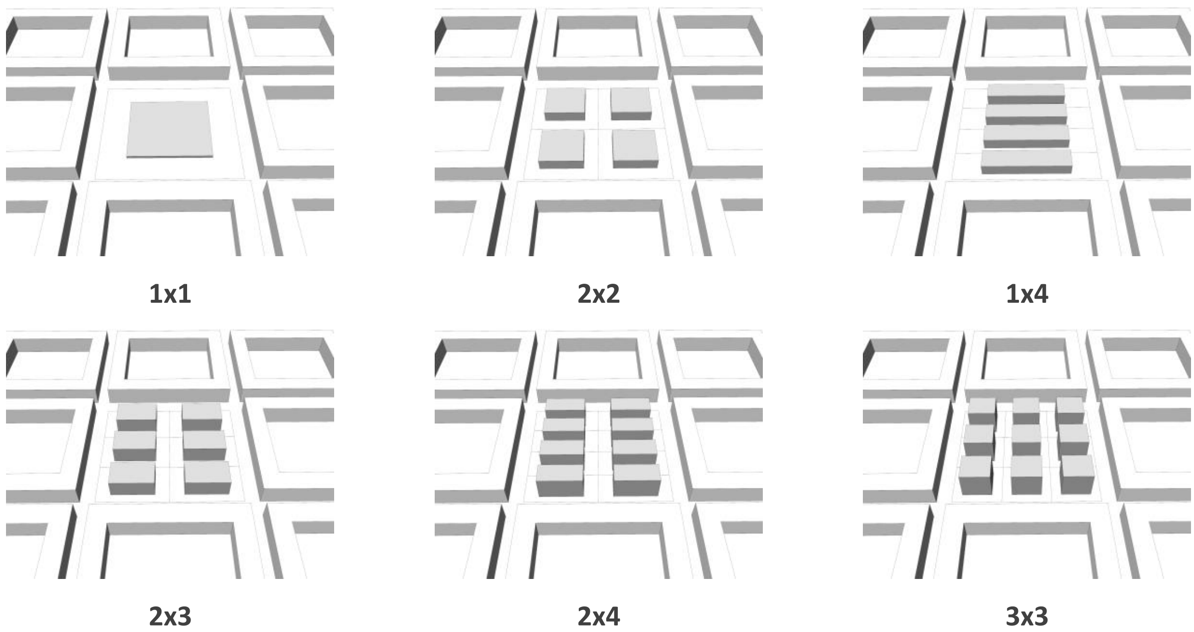


Fig. 107. Dynamic parceling options, based on values set for subdivisions along the *X* and *Y* dimension. Building units came with the following steps; by now, it is sufficient to say that units are sensitive to both subdivision pattern and plot ratio, but the two conditions are independent from each other. The quantity of volume is constant across the pictures (source: author).

[140] Available at http://www.food4rhino.com/.

[141] A complexification measure we have endorsed to bring value to pattern formulation, dumping overly simplified solid-void structures (see section 3.4).

The horizontal occupation of the tester block has been expressed as coordinate pairings relativized to every parcel. These couples of coordinates inform both size and location of E-W and N-S sides of a built surface. *X* and *Y* coordinates have been related to four point constructors two-by-two so as to arrange inscribed rectangles.
We are aware that the choice of inputs represents a decisive moment of responsibility for human elements, for it relates to the whole stream of subsequent (*dependent*) operations and reflections with a strongly deterministic power. Compelled by such determinism of data flows, we chose to adopt the highest level of information that context geometric operators could sustain, based on our knowledge of *Grasshopper*.
At first, one might consider the alignment of street frontages or soil sealing as inputs for effectively informing occupation. The reality of parametric modeling tells us that these are ambiguous measures, because neither of them would control space obstructions with unequivocal determinacy. In this sense, we should remember the fundamental property of *unambiguity* characterizing every algorithm[142]. The percentage of built frontages facing the street can only *describe*, rather than properly *control* occupation choices: the same value could relate to radically dissimilar patterns of form, because percentages do not have a univocal correspondence with layout options. Alternatively, diverse patterns may end up with the same percentage value. This 1-*N* relationship can be observed even when dealing with soil sealing coverage, for pretty much the same reason. This aspect makes 1-*N* measures suitable for being *indicators*, rather than parameters of the system: as such, they come as consequences of occupation.
A second alternative could have been generating random numbers for point locations, but, as we have seen in the case study *A*[143], randomness, despite being legible for the system, is not as intuitive for the human element, because it does not restore any clear connection between pattern of occupation and its effects in terms of efficiency. Besides, it leaves very little room for awareness and responsibility in controlling patterns. Through the computational architecture of *Grasshopper*, random values would have changed "liquidly" to support a wider gradient, but with no *trackable* formulation. In brief, a formulation more representative of designerly choices. Hence, 0-1 "coordinates" of occupation have been considered as the most appropriate input format for achieving both intuitiveness and precision at once.

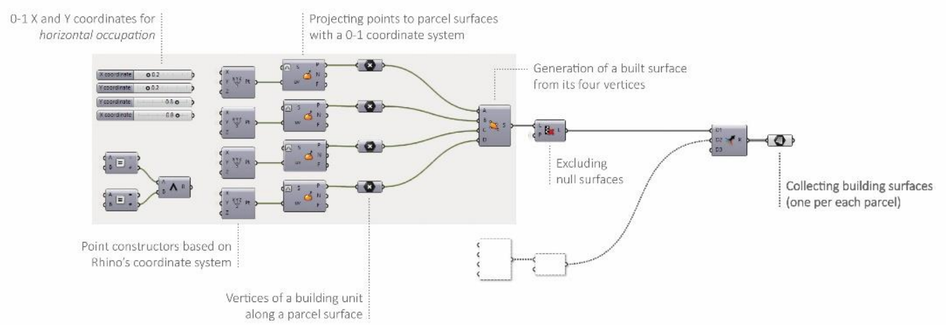


Fig. 108. The sub-matrix assembled for generating one built surface per each parcel. The definition we see has been replicated for every parcel, in this case nine times (source: author).

List of input data	List of output data
Surface geometries of single tester parcels (*stored*) Pairs of *X* and *Y* coordinates of *H* occupation (*sliders*)	Surface geometries of built coverage, one per parcel

Tab. 9. Synthesis of what the subset required (input information) and produced (output information) for the generation of built surfaces (source: author).

142 Discussed in section 1.2.2.
143 See section 3.1.3.

According to our definition, horizontal coordinates could even contemplate the elision of one or more bases, ending up with fewer units that would always inherit the volume lost (see *figure* X). Parcel generation worked with submultiples of the plot; here, the 0-1 format of horizontal occupation differentiates *X* and *Y* dimension, entailing that each building base is not a perfect submultiple of its parcel, but a proportion to total length and width of that same parcel.

Through a pair of number *sliders* per axis of occupation, we could govern the proportion of N-S and E-W sides to, respectively, *X* and *Y* extent of the parcel, linking the four levers to four vertices based on a two-by-two pattern. Measuring such proportion in terms of absolute length along parcel and plot borders led to a straight-forward calculation of street alignments (*natural surveillance*).

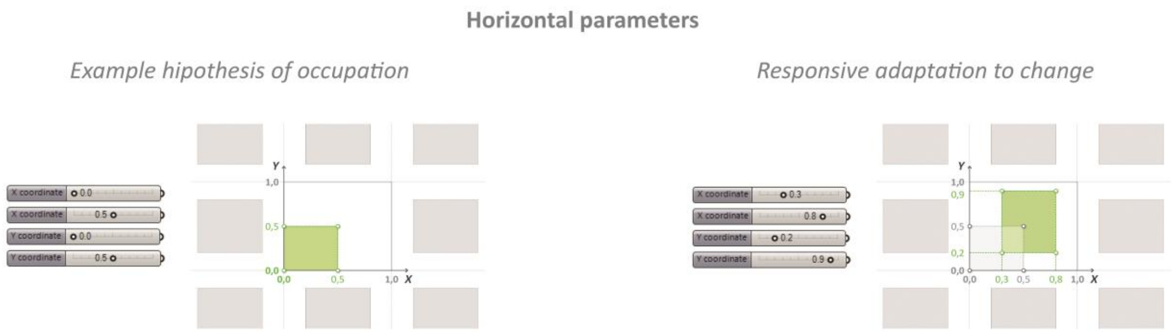


Fig. 109. A more explicit view of how horizontal 0-1 coordinates worked in relation to the reference system of each parcel surface, leading to the generation of built surfaces (source: author).

Fig. 110. Two examples of occupation banking on the independent nature of each unit, which lay, in turn, on subset replicas carried out for each parcel: a regular arrangement (on the left) and an irregular one (on the right). In this case, "regular" and "irregular" are simple judgements of human observers; in contrast, the machine interprets both instances as results of the same freedom in manipulating units separately (source: author).

Unlike the horizontal dimension, we opted for translating the idea of vertical occupation through a single parameter describing the ratio of total volume to plot area. This came at the expense of an even distribution across units. However, the idea also consists of a likewise intuitive definition for complying with design demands[144].

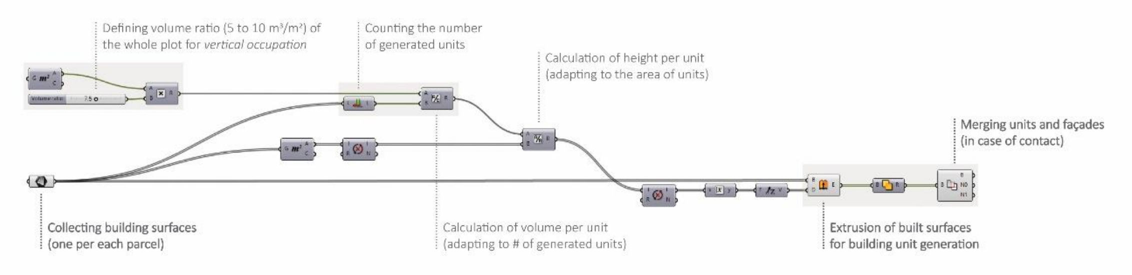


Fig. 111. The sub-matrix assembled for generating total volume as a vertical measure, and intersecting it with each built surface generated horizontally, so as to produce the building units forming our parametric block. This step represented the "stepping-stone" prompting the input for evaluative terminals (source: author).

List of input data	List of output data
Surface geometry of the tester plot (*stored*)	Volume geometries of units of the tester block
Surface geometries of built areas per parcel (*stored*)	Total volume of the tester block
Volume ratio for tester block (*slider*)	

Tab. 10. Synthesis of what the subset required (input information) and produced (output information) for the attribution of volume and the subsequent generation of building units (source: author).

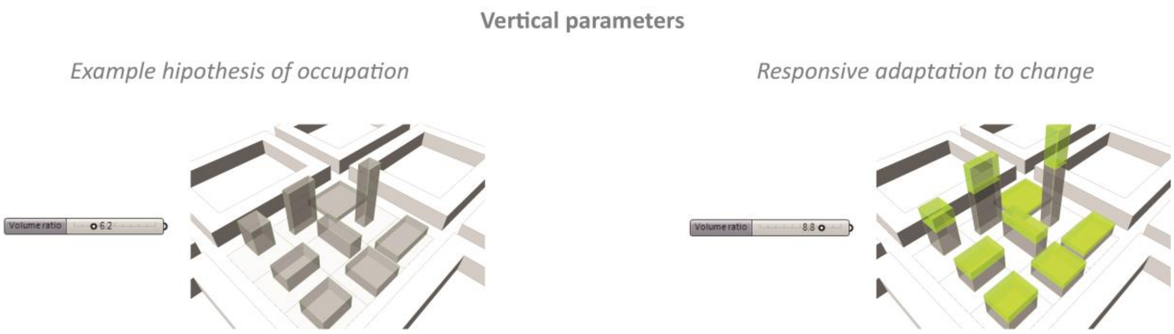


Fig. 112. A more explicit view of how our vertical parameter of volume ratio worked in relation to building units. Every volume quantity within the chosen range of 5 to 10 m^3/m^2 would equally distribute sub-portions across single bulks, independently from their horizontal occupation: the green volume increments we see on the left describe exactly the same quantity, with different effects on morphology as a whole (source: author).

The algorithmic subsets composed for block formulation have been conceived in such a way that they enabled three noteworthy properties of our parametric environment: elasticity to perimeter distortions, volume culling and redistribution, solid unions and merge of façades (*fig.* X). Each one of them reproduced a different nuance of complexification and, to a certain extent, specific quality.
The first property lay on our choice of relativizing horizontal coordinates to parcel surfaces, projecting building vertices to a normalized reference system. Such normalization stack vertices to a reparameterized domain,

[144] In fact, controlling development through changing the volume ratio guarantees the exactitude of quantitative loads in respect to likewise mutable requisites of plans or competitions. At the same time, this opportunity would be grounded on a well-rooted measure for architectural and especially urban composition.

whose grid would "*stretch*" according to ever-new margins. The second property has found its reason for being in the act of joining the elision of null surfaces, something actually within the reach of available values[145], with a reactive (or *responsive*) count of generated units. Each unit assumes the same portion of volume, calculated dividing total volume by the number of units. Injecting the automatic recomputation of such number into the portioning process allowed for saving and reallocating the volume lost with elision throughout the remaining units. The third property has been possible through in-built operators, whose role was acquiring extruded units and submitting them to the merge of volumes and envelops whenever they touched along parcel borders. This has been useful to overcome the restraint of parcels as "bounding boxes" of buildings, at least partially. In this way, different and numerous opportunities of conglomeration and composite spaces have been included in the gradient, with no loss of consistency for isolated units.
At the top of the figure, we see the assumption of initial pattern instances; at the bottom, we assist to mutations that, by the way, are not mutually exclusive. In fact, the first mutation (in the bottom left corner) contemplates distortion as well as culling the central unit and merging the others in different ways.
We should remember three characters, one per property. The first is that distorting the grid does not affect coordinates of occupation, because these, other than being totally independent, pertain to the normalized reference system of parcels: what they inform (or govern) is not the absolute, global position of building vertices, but their relative, local position in relation to respective parcels. The second is that volumes culled in the second column are equally reallocated to "surviving" units, due to the even subdivision of general density loads across the units. The third is that merging item units implies the automatic update of the model in terms of number of generated buildings and number of faces per unit, which excludes coinciding walls and restores the integrity of the envelop as a unique geometry. This latter aspect has been crucial especially for sorting radiation results while always keeping the important correspondence between datum and respective geometry.

Fig. 113. Representation of geometric properties characterizing and expanding pattern formation compared to case studies. Each of them relied on precise constraint definitions for the matrix (source: author).

[145] In effect, our definition made possible to match either or both *X* and *Y* coordinate values in a way to annihilate surface generation just as another possible alternative of occupation. Elisions come about as either or both pairs of coordinates assume, singularly, the same value, leading to the perfect superimposition of building sides and, as a consequence, the vanishing of the building surface.

The "nerve ending" of the algorithm consisted of five subset solvers that, starting from generated surfaces and extrusions, have been designed to appraise block geometries *responsively*, thus carrying out a multi-polar evaluation of efficiency. Definitions for these terminal sectors have been constructed through combining geometrical, mathematical and data management components so that they could translate five indicators of reference into algorithmic syntax. This happened recognizing that formulas are, in effect, just alternative forms of algorithms, because they instruct the treatment of precise data according to *unambiguous* language. This language corresponds, in their case, to pure mathematics. Untangling such formulas has been crucial for expressing the procedural sequence in a way that could be intelligible to *Grasshopper*.

Here, we find the operative "decryption" of measures that have been selected according to the critical interpretation of case studies[146]. The five indicators are composed of two energy measures, *compactness* (α) and *solar energy density* (β), and three complementary measures of morphometry, acting as those distortion factors that demand certain arrangements of occupation, which are *natural surveillance* (γ, horizontal), *diversity of heights* (δ, vertical) and *spaciousness* (ε, horizontal and vertical)[147].

Compactness (α), a simple, yet good estimator of heat loss propensity, has preserved its meaning of surface to volume ratio, in adherence to suggestions of literature (Baker & Steemers, 1992; Lobaccaro et al., 2016). The expression below refers to the average compactness of the whole tester block, but disaggregate values have also been preserved for appraising single units:

$$\alpha = \frac{\sum_i^n \left(\frac{S_i}{V_i}\right)}{n}$$

Where S_i is the envelop surface [m^2] of unit *i*, V_i is the volume [m^3] of unit *i* and *n* is the pure number of units spawned by the matrix, so the overall unit of measure is [m^2/m^3]. Increasing *compactness* means reducing as much as possible the quantity of envelop area per unit of volume, i.e. dragging the average value to zero. This is also in line with our "struggle" for well-balanced densification, because nearly zero values approach a situation where the pressure of volumes meets the pressurization of envelops at the equilibrium point.

Through a concatenation of geometry and mathematical operators, we could translate the calculation stream of *compactness* to algorithmic syntax. The context vocabulary of preset components proved to be sufficient for handling the important step of recycling façades as new input for intersecting the value of volume per unit with measures of envelop surface, which could vary according to occupation coordinates.

Similarly to what happens with other indicators, the evaluation circuit starts with the set of units that had been generated through extrusions and solid union. Here, we have two parallel sequences: one relates to re-computing volume per unit, which is verified as equal for the whole block, whereas the other consists in deconstructing unit geometries and capturing their clusters of faces, which have been quantified in terms of area afterwards.

The set of areas computed for building faces has been processed through mass addition to get the area of envelop surface per each unit, now fitting for the indicator. The two data streams have been collected towards arithmetical division, following the formula. In essence, the algorithm is no more than a procedure unwrapping the meaning of the indicator. Through a component for color gradients, we could match valuation results with a real-time preview.

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[146] Justified and anticipated in the previous section.

[147] In particular, four out of five indicators required importing the volume geometries of the tester block; *natural surveillance* found sufficient information in built surfaces, due to the interest in 2D occupation. This structure led to no contradictions at all, because dependencies described perfect coincidence between sides of built surfaces and the extent of final volume geometries, making all measures consistent one with the other.

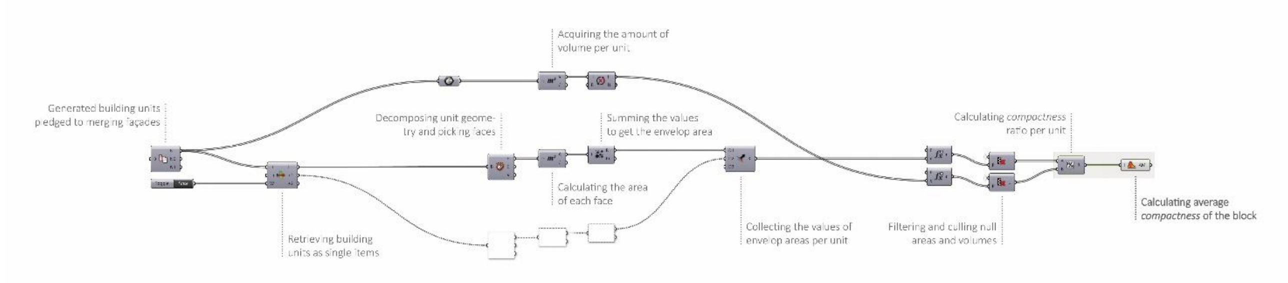

Fig. 114. The sub-matrix assembled for engineering the evaluation of *compactness*, which led to the average value at block level passing through calculations made for each generated unit (source: author).

List of input data	List of output data
Volume geometries of units of the tester block (*stored*)	*Compactness* of tester units and block average

Tab. 11. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of generated form in terms of *compactness* (source: author).

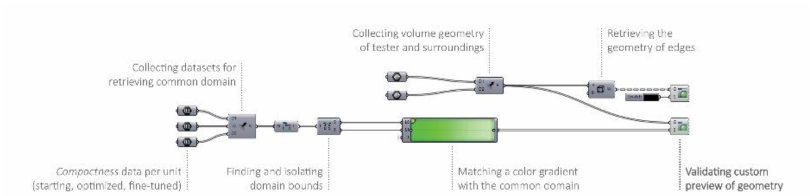

Fig. 115. The sub-matrix assembled for reproducing a dynamic 3D preview of *compactness* degrees per unit. This kind of definition is not a secondary aspect of abstraction, because having an intuitive feedback for human eyes would be highly beneficial to the real-time awareness of changing occupation choices (source: author).

List of input data	List of output data
Volume geometries of units of the tester block (*stored*) *Compactness* values per unit per scenario (*stored*) Anchor color tones and 0 to 100 positions (*stored*)	Preview of color shades per unit, based on *compactness*

Tab. 12. Synthesis of what the subset required (input information) and produced (output information) for dynamic 3D visualization of *compactness* degrees (source: author).

The second energy indicator chosen is *solar energy density* (β), and describes the efficiency of envelop systems in harvesting solar radiation per unit surface (Lobaccaro et al., 2016). The procedure of calculation worked on building faces and comprised values per face per unit, aggregate values per unit and average value of the tester block as a whole. Such complex measure required using a specialized *plugin* for solar simulation. For this purpose, we used *DIVA* 4.0 set of custom components[148]. The following expression refers to average *solar energy density* at tester block level:

$$\beta = \frac{\sum_{i}^{n}\left(\sum_{j}^{m}\frac{E_{ij}}{S_{ij}}\right)}{n}$$

[148] Available at http://diva4rhino.com/.

Where E_{ij} is the quantity of solar energy [kWh] received by façade *j* of unit *i* in one year, S_{ij} is the surface area [m^2] of façade *j* belonging to unit *i*, *n* is the number of units and *m* is the number or façades, thus the indicator is measured in [kWh/m^2y]. In this study, we chose not to endorse any particular building face. Actually, focusing on either or both South and zenithal portions of envelop systems would have been useful for engineering passive and active strategies directly from a generative perspective. Of course, grounding the appraisal on full envelops has had an influence in both formulation and interpretation of outcomes, just as what happens with any valuation process, and this amounts to the responsibilities of designers in a context of *user-defined* rulesets. The indiscriminate view of envelop systems led us to recognize, although implicitly, that higher values of mean *solar energy density* would connote those arrangements able to harvest radiation as much as possible even toward East, West and North orientations. However, this aspect did not contradict the supremacy of South and zenithal faces in determining the overall value.

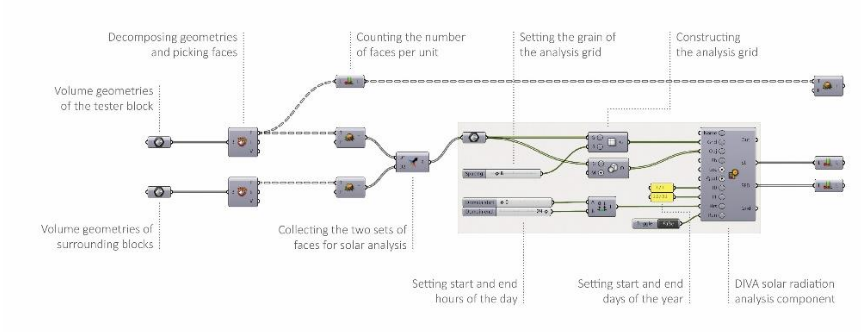

Fig. 116. The sub-matrix assembled for engineering the evaluation of *solar energy density*. The use of *DIVA*'s specialized components also allowed for including absolute values of radiation. This has been the first part of the energy evaluation flow, which made explicit reference to important settings, such as time period and accuracy, but ended up with raw data only, implying the need for symbiotic data management branch (source: author).

List of input data	List of output data
Volume geometries of units of the tester block (*stored*) Volume geometries of surrounding blocks (*stored*) Grid resolution for energy analysis (*slider*) Period of time for energy analysis (*slider*)	Aggregate values of absolute *solar energy* per each face Aggregate values of *solar energy density* per each face

Tab. 13. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of generated form in terms of *solar energy density*. Absolute *solar energy* has been included for completeness (source: author).

Though average solar energy density has been taken as the criterion for tuning and optimization, *DIVA* allowed evaluating the design against solar capture as an absolute measure.
In any case, the analysis component required specifying common spans of calculation (we proposed the whole year, 24h), material options (here: generic façade with 0,3 *albedo*, as our interest is pure geometry) resolution, a choice based on computing power (a coarser spacing option for the analysis grid, as described in figure X) and, finally, location-based weather data. In this case, we loaded the open source data registered for the city of Milan[149].

[149] Retrieved from https://energyplus.net/weather.

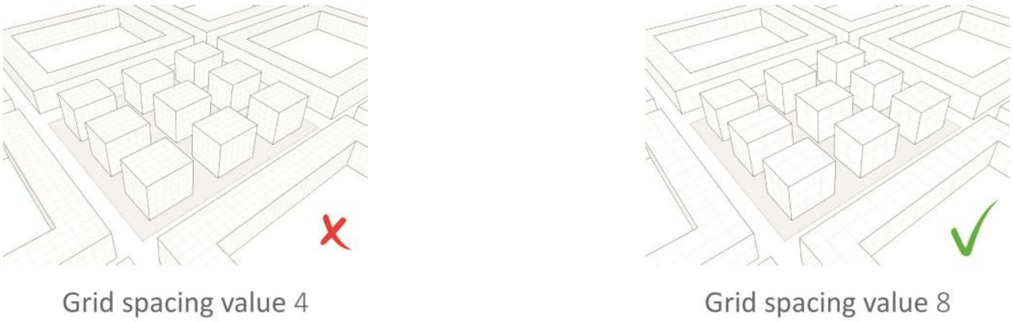

Fig. 117. Extraction of two hypotheses of grid resolution for detailing energy analysis. *DIVA*'s parameter quantifies the "texture" or the grain of simulated sensors upon the set of imported faces: the smaller the number, the finer the grain, the sharper the computational strain. Having a demanding process of optimization on sight, this latter reason suggested a coarser grid (source: author).

As *DIVA* could not appraise tester and nearby blocks separately without neglecting one of the two, the reduction of edge effects called for both inputs at once, which implied the demand of an adaptive selection system for output solar data. In fact, we were not concerned but with the capacity of our tester block to re-shape itself according to the values it reflected. In this respect, this has been a partial experiment due not only to consistent, though necessary simplifications, but also to the (conscious) exclusion of surrounding impacts from the computation of (optimal, tuned) volume arrangements. Perhaps, parametric form would behave differently if solar externalities were to be factored in the process.
The in-built indexing logics played a role in this case, as well as the number of façades per unit, which has been indispensable with merging buildings. An inconvenient linked to bottom faces, which do not share the same item index in case of solid unions, has been solved by culling the least possible radiation receivers.

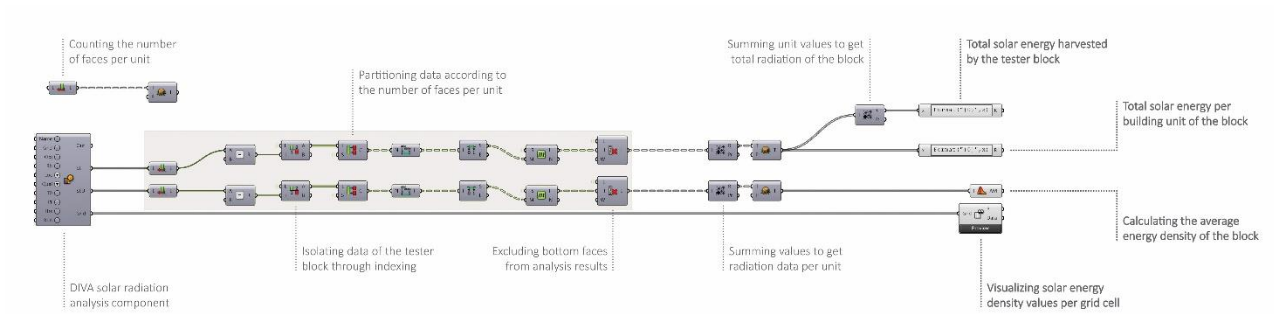

Fig. 118. The sub-matrix forming the "architecture" of outbound data treatment, playing as an essential appendix to the energy solver. Note that counting the number of faces per generated unit dynamically has been decisive for preserving the exact correspondence between datum and unit: a necessary abstraction within a context allowing for mutable and manifold solid unions (source: author).

List of input data	List of output data
Aggregate absolute *solar energy* per façade (*stored*)	Total absolute *solar energy* received by the tester block
Aggregate *solar energy density* per façade (*stored*)	Total absolute *solar energy* received by each tester unit
Number of faces per unit of the tester block (*stored*)	*Solar energy density* received by each tester unit
Number of faces of surrounding blocks (*stored*)	Average *solar energy density* of the tester block
	Preview of color shades per face, based on *solar density*

Tab. 14. Synthesis of what the subset required (input information) and produced (output information) for selection, organization and treatment of raw *solar energy density* data, as well as dynamic 3D visualization through color gradient on building faces. Absolute *solar energy* has been included for completeness (source: author).

In respect to the experiment of optimization, we decided to fulfil the generalization of performance enabled by *digital parametrics*. In particular, this "slice" of the algorithm owes a cultural debt to the housing optimization study carried out in Trondheim, Norway (Lobaccaro et al., 2016). Our version articulates a very similar strategy when it comes to using *Galapagos* as a heuristic solver. Let us consider the expression:

$$f_{max} = max\left(\frac{\beta}{\alpha}\right)$$

Where α is the average *compactness* [m^2/m^3] and β is the average *solar energy density* [kWh/m^2y] of our tester block, thus the *fitness* is measured in [kWh/my]. Despite the ratio between solar density and compactness has no clear meaning as a standalone measure, for we do not consider any prediction of energy balance by now, it depicts an insightful dodge bypassing single-objective optimization by use of a simple mathematical relationship. Setting maximization for this fitness would mean calibrating the two indicators so that solar capture rises with volume and envelops undergo compression. Through manipulating the genome of occupation, *Galapagos* achieved a significant twist of horizontal and vertical properties.

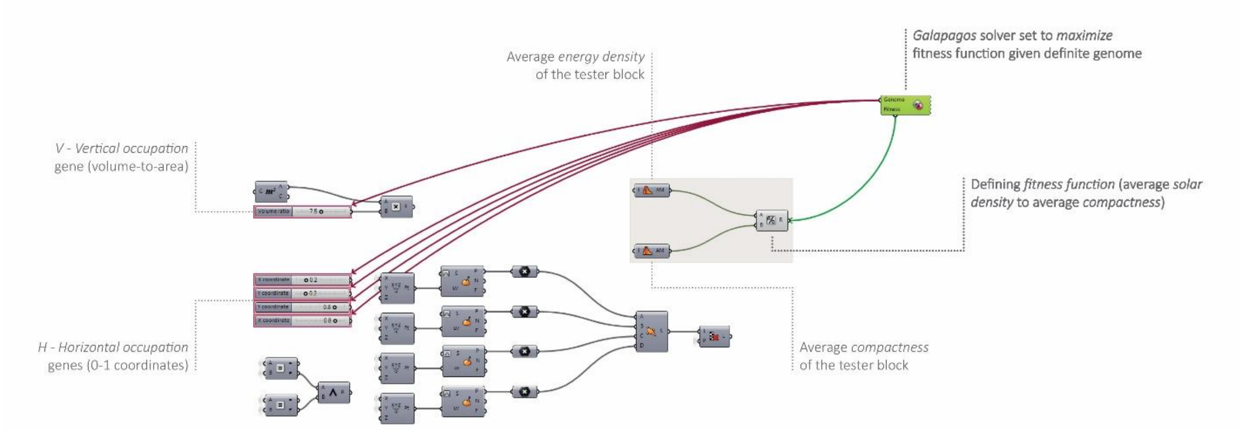

Fig. 119. Selection of the elements performing as *genome* (red) and fitness (green) for the optimization solver (in this case, David Rutten's *Galapagos*). *Average energy density* and *average compactness* of the block were *responsive* functions of parameters governing horizontal and vertical occupation of units. Within the optimization cycle, parameters became the genome to be manipulated in search of ever more satisfactory forms; the ratio of average energy density to average compactness became the *fitness* to be maximized, which served as an unceasing feedback for improving satisfaction. The number of cycles has been stopped to 30; the number of generations per cycle has been set to 20 (source: author).

Fitness construction	
List of input data	**List of output data**
Average *solar energy density* of the tester block (*stored*) Average *compactness* of the tester block (*stored*)	*Fitness* ratio (mean *solar density* over mean *compactness*)

Optimization process with Galapagos	
***Genome* for mutation**	***Fitness* criterion for feedback**
X and *Y* coordinates of horizontal occupation (*sliders*) Volume ratio for vertical occupation (*slider*)	*Maximum* for mean *solar density* over mean *compactness*

Tab. 15. Synthesis of what the subset required (input information) and produced (output information) for the *fitness* function of evaluation (at the top); the parameters used as *genome* and the *fitness* criterion set for optimization feedback (at the bottom) (source: author).

Natural surveillance is the first ancillary factor of occupation we considered, and it detects the potential degree of visual control over a space with some approximation. In reality, we can consider this indicator as a *proxy* for quality urban design development, where streets claim a primary role of public and social spaces that are not only pledged to mechanical movement.
The literature endorses this feature of urban form as an influent, though not deterministic condition of a legible, bracing and secure urban place, channeling people toward encounter while clarifying the interface between private and public lives with an expressive scenography (Carmona, 2010; Jacobs, 1961; Porta & Renne, 2005).
The evaluation considered the following formula:

$$\gamma = \frac{F_s}{P_b}$$

Where F_s is the length [m] of unit frontages facing the street, and P_b is the perimeter [m] of the tester block, i.e. the length of surrounding street. The proportion has been multiplied times 100 to get the percentage expression [%]. Knowing the appeal of a public scene framed across its perimeter line, we could consider *natural surveillance* as a call for horizontal obstructions of space, which may alter solar access to different extents. Our system of values could classify and interpret outcome morphology according to definite ranges of *natural surveillance*, i.e. definite portions of the 0-100 scale. We considered a 0-50% range as unsatisfactory; a 50-75% range as good and a 75-100% range as excellent.
Even in this case, we remember that each algorithm should be read from left to right, as seen in our theoretical framework. Despite the seemingly simple formula, the calculation required a quite articulate, though methodical subset (*figs.* X, X and X), based on the extensive selection of edges from built surfaces. These surfaces have been exploded to get constitutive edges. This process banked a lot on in-built indexing of edges: the ones concerned with being parallel to the outline of the plot had to be isolated according to their respective indices. In particular, we could distinguish three situations based on our 3x3 parceling system: corner units, midway units and central unit. The first type required picking two sides, the second only one side, while the third, that is, the unit having no adjacency to plot perimeter, has been excluded through disconnection of wires. As these curves have been extracted, stored and grouped according to the unit of reference, the process demanded duplicating the flow: on one hand, funneling geometries toward direct calculation of the percentage at block level (*fig.* X), and, on the other, keeping single edges to compute percentages at unit level (*fig.* X).
In the first case, concerned edges per unit have undergone measurement and total summation; in parallel, the length of tester plot perimeter has been obtained. The ratio of the former to the latter product returned the value of surveillance for the whole block.

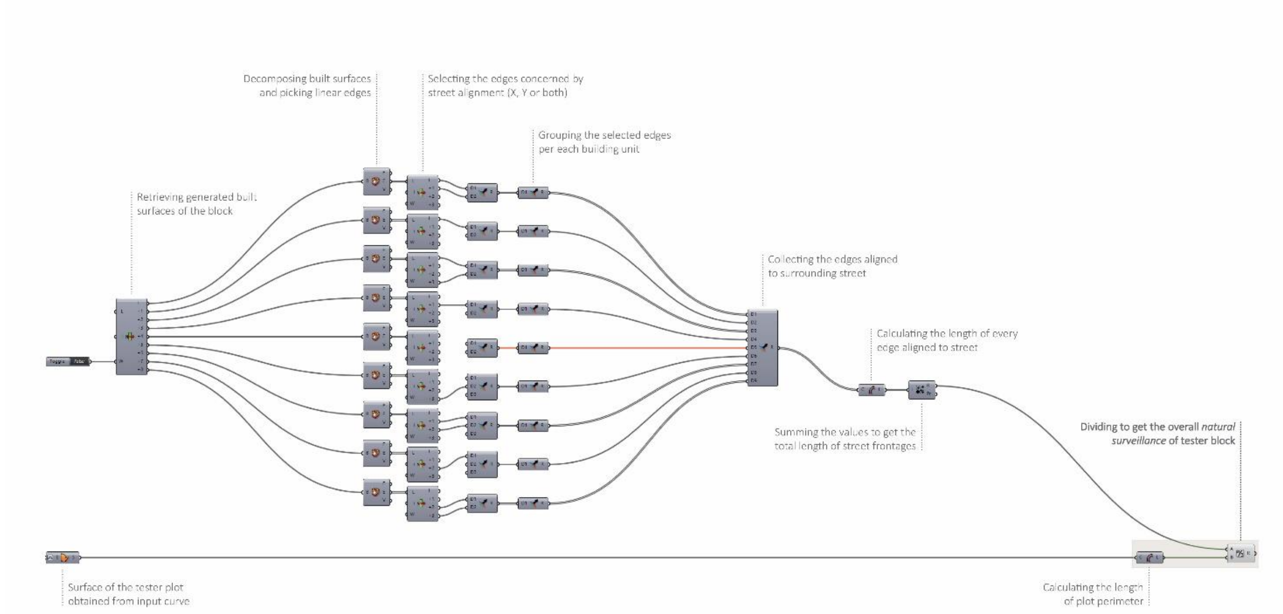

Fig. 120. The sub-matrix assembled for engineering the evaluation of *natural surveillance*. In particular, this has been the first part of a wider calculation process. Here, the selection of built edges concerned with "framing" the street led to the evaluation for tester block as a whole, summing all values per unit at once. The orange wire in the middle stands for absence of data and corresponds to the unit excluded for being not adjacent to block border (source: author).

List of input data	**List of output data**
Surface geometries of built coverage per parcel (*stored*) Surface geometry of the tester plot (*stored*)	*Natural surveillance* of the tester block

Tab. 16. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of generated form in terms of *natural surveillance* of the whole block (source: author).

In the second case, a further definition has been required, because it lay on the *X* and *Y* extent of single parcels. These extent measures were common to any parcel; therefore, we retrieved the two representative values of the distribution, one for *X* and one for *Y*. Based on the distinction between corner and midway units, these values would set two different benchmarks, i.e. maximal lengths of reference. Street-lined edges of corner units would insist on the sum of *X* and *Y* extent, while the ones of midway units would represent a proportion to, alternatively, *X* or *Y* extent. Selected curves per unit have been metered separately in all cases; corner units called for summing their value couples to get the absolute length along respective street portions. The individual degrees of surveillance have been obtained dividing every length value by corresponding benchmarks. Starting from a selection of concerned edges per unit, we considered circumscribing them through "pipe" geometries to get a visible preview.

Compared to definitions conceived for all the other measures, the "architecture" built for *natural surveillance* showed one strong limit of adaptability, though lying on a very elementary formula. The clue of this limit could be traced to the scarce automatization of selectors, which has been loosely compensated through the personal recognition of the "right" geometries. In fact, the interpretation of parallelisms between building and plot/parcel borders has been left to the human eye, and not, for example, to an automatic solver for topology.

Let us consider, for instance, the hypothesis of changing the number of plot subdivisions. Altering the grain of parcels would result in extremely variable relocations of units, implying the manual (and costly) adaptation of each wire of the subset. Buildings would assume different relationships with the street at every recomputation: midway units may convert to corner units, and *vice versa*. Some may be transferred from bordering parcels to central ones or the other way round, with relevant effects on the behavior of surveillance. The calculation would lead to erroneous results if we kept the same definition for the appraisal of diverse parceling systems, especially in imaginary cases where recursive optimization cycles insist on natural surveillance while considering sliders for block subdivision as an integral part of genome.

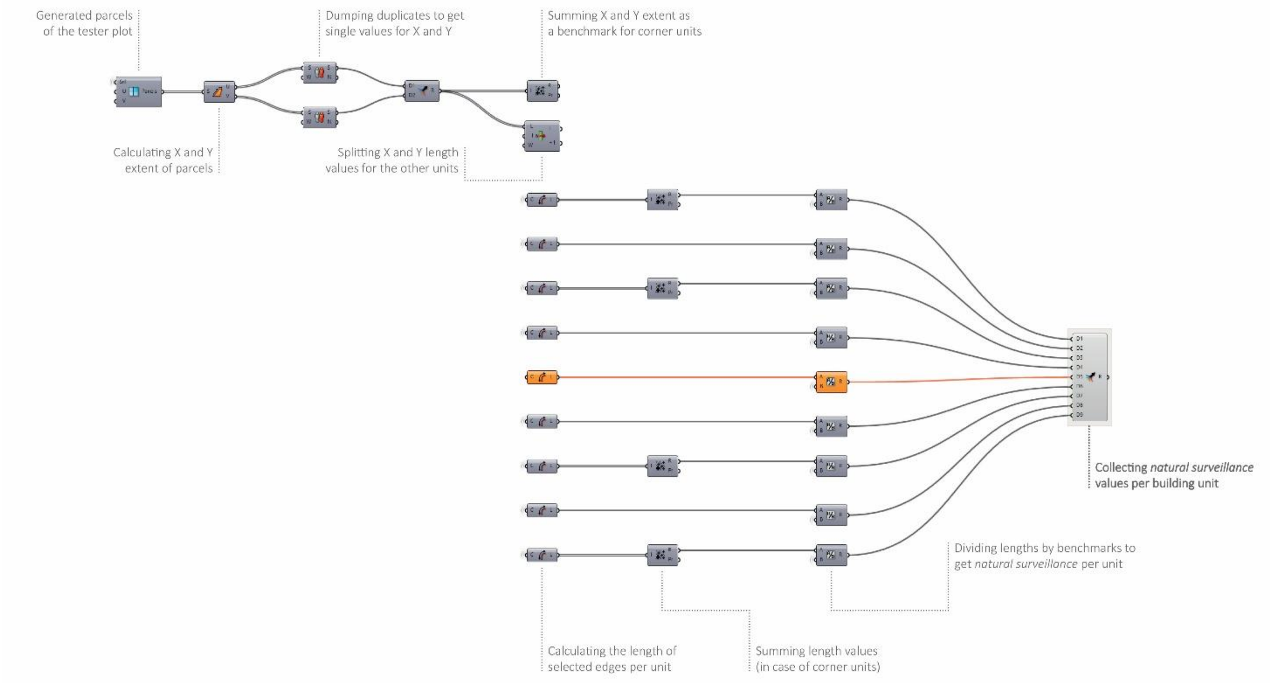

Fig. 121. The sub-matrix assembled for engineering the evaluation of *natural surveillance* at the level of single units. This has been the second part of the calculation process, which required distinguishing benchmarks for corner and midway units. Again, we find the orange collector we have seen in the previous figure, which stands for the data flow interrupted for the central unit (source: author).

List of input data	List of output data
Surface geometries of parcels of the tester plot (*stored*) Curve geometries of built edges facing the street (*stored*)	*Natural surveillance* of each unit of the tester block

Tab. 17. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of generated form in terms of *natural surveillance* per unit (source: author).

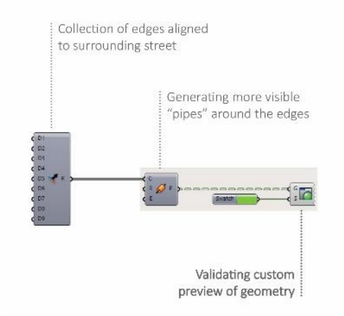

Fig. 122. The sub-matrix assembled for reproducing a dynamic 3D preview of *natural surveillance* at unit and block level. Simple "pipes" have been generated around built edges parallel to block outline and the street, so as to have at least the clue about the general proportion of street-lined faces over block perimeter at each change of patterns (source: author).

List of input data	List of output data
Curve geometries of built edges facing the street (*stored*) Radius extent of "pipes" for preview (*stored*)	Preview of "pipes" around the edges facing the street

Tab. 18. Synthesis of what the subset required (input information) and produced (output information) for dynamic 3D visualization of building edges facing the street, i.e. tester plot outline (source: author).

The second ancillary factor of occupation is *diversity of heights*. It portrays a rough estimation of visual variety and "perceptive pace" through a certain degree of heterogeneity in the third dimension. Height diversity, which strictly depends on both horizontal and vertical parameters, also considers the essence of complexity as a driver of a self-sustained adaptability to different uses and change, in contrast with radical homogenizations of seemingly "rational", but unattractive urban landscapes. The indicator proposed is nothing more than the *variation coefficient* of building heights, i.e. a standard deviation relativized to the average value, which becomes suitable for comparing diversity grades across scenarios that differ for vertical magnitude:

$$\delta = \frac{\sqrt{\frac{\sum_i^n \left(\bar{h} - h_i\right)^2}{n}}}{\bar{h}}$$

Where h_i is the height [m] of building unit i, $\bar{h}$ is the average height [m] of units and n is the pure number of generated units. The indicator is a pure number as well. Statistical knowledge found in Corbetta (2003) helped the interpretation of this measure through the distinction of three intervals: 0-0,5, corresponding to moderate diversity; 0,5-1,0 (excluded[150]), corresponding to sizeable diversity; and more than 1,0, corresponding to massive diversity.

Just as what we have seen with the calculation of *compactness*, this measure has found its translation in *Grasshopper*'s basic mathematical components: again, the algorithm performs as no more than an explicit and procedural view of how we would apply that formula. Custom syntax expressions like square deviations between two inputs (here: height values per generated unit and average height of the block) concurred to speed up the calculation with less components.

[150] The *variation coefficient*, or *relative standard deviation*, can never be equal to 1 (Corbetta, 2003), because average and standard deviation cannot converge to the same value.

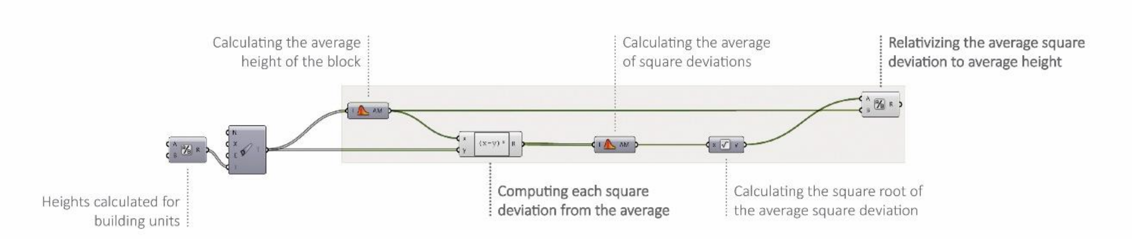

Fig. 123. The sub-matrix assembled for engineering the evaluation of *diversity of heights*, done untangling the calculation process through the combined use of basic mathematical components. All operators were already embedded in Grasshopper; originally, the one calculating single square deviations (fourth from left) was a component supporting custom expressions to be written in pure mathematics (source: author).

List of input data	List of output data
Values of height per unit of the tester block (*stored*)	Average height of the tester block Square deviations from the average height per unit *Height diversity* (variation coefficient of building heights)

Tab. 19. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of *height diversity* (source: author).

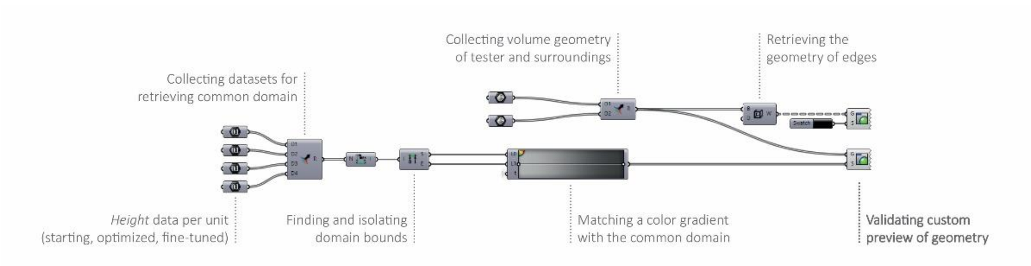

Fig. 124. The sub-matrix assembled for reproducing a dynamic 3D preview of heights per unit. As with the one designed for degrees of *compactness*, this definition would give a straightforward feedback for flexible representation and facilitated interpretation of obstructive properties (source: author).

List of input data	List of output data
Values of heights per unit per scenario (*stored*) Volume geometries of units of the tester block (*stored*) Anchor color tones and 0 to 100 positions (*stored*)	Preview of color shades per unit, based on height value

Tab. 20. Synthesis of what the subset required (input information) and produced (output information) for dynamic 3D visualization of height values (source: author).

After considering horizontal and vertical factors separately, their combination into a horizontal and vertical measure has been carried out with a third complementary indicator. *Spaciousness* is soundly sensitive to how density relates to different shapes and solid- void systems. Specifically, it connects the volume with the amount of open space left free from soil sealing (Berghauser & Haupt, 2010), which worked as a pretext for calculating *covered ratio* as well.

In contrast with volume ratio, spaciousness helps calibrating the amount of open space per volume, depicting the extent to which voids act as decompressors of solid impacts, something that influences the density of human experience across open spaces. Here we only consider the generic open space of the block for applying the formula:

$$\varepsilon = \frac{A_t - A_c}{V_t}$$

Where A_t is the total area [m^2] of the whole block, A_c is the covered area [m^2] of the whole block, V_t is the total volume [m^3] of the whole block. The value has been multiplied times 3 meters of interfloor for a more intuitive scale (Berghauser & Haupt, 2010) using equivalent floor area [m^2/m^2]. The interpretation of values drew indications from *corrected compactness*, a further indicator that, excluding criteria of open space selection, happens to be the reciprocal measure of spaciousness, measured as volume to open space [m^3/m^2]. The evaluation protocol in Puerari (2011) helped tracking a possible partition of values of corrected compactness into three intervals: less than 3, 3-6 and more than 6 m^3/m^2. Calculating the reciprocals of these thresholds, inverting the scale of values and adapting the measure to equivalent floor area[151], we get three intervals for spaciousness: less than 0,6 m^2/m^2, corresponding to extreme compression, 0,6-0,9 m^2/m^2, corresponding to tolerable compression, and more than 0,9 m^2/m^2, corresponding to adequate compression.

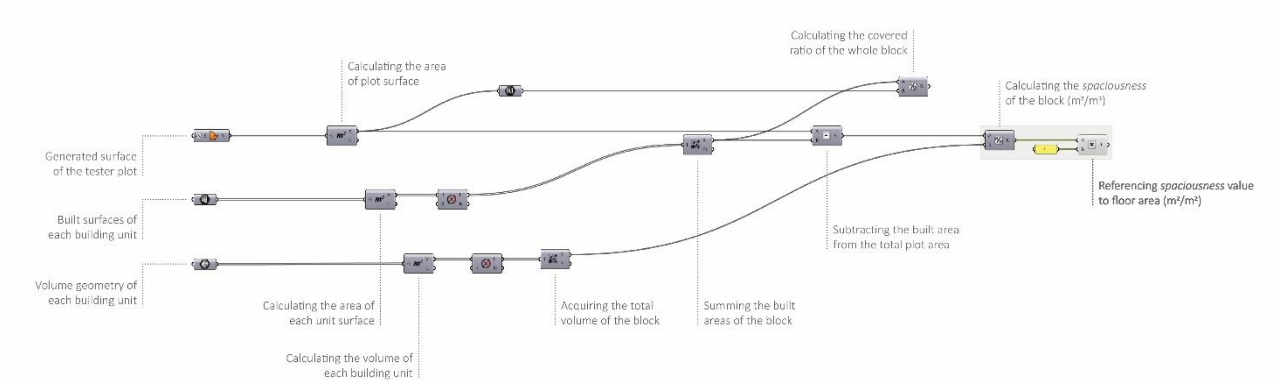

Fig. 125. The sub-matrix assembled for engineering the evaluation of *spaciousness*. The process started from the parallel quantifications of tester plot area, total built area and total volume (which had already been fixed through the parameter of plot ratio). The first two led to the calculation of our generic open space. Dividing open space area by total volume served to define volume-scaled spaciousness, which has been finally transposed to a scale based on floor area by triplication of the value. The stream also favored the responsive extraction of *covered ratio* at block level (source: author).

List of input data	**List of output data**
Surface geometry of the tester plot (*stored*)	*Spaciousness* of the tester block using volume [m^2/m^3]
Surface geometries of built coverage per parcel (*stored*)	*Spaciousness* of the tester block using floor area [m^2/m^2]
Volume geometries of units of the tester block (*stored*)	Covered ratio of the tester block

Tab. 21. Synthesis of what the subset required (input information) and produced (output information) for the appraisal of *spaciousness* at block level (source: author).

[151] That is, multiplying the obtained values times 3 meters of interfloor.

In this case, the unexpected choice of a nearly optimal starting scenario led to a refinement rather than a drastic enhancement of compactness and solar capture. Anyway, we can still appreciate the effort in sharpening occupation efficiency, as the algorithm enabled performative increase while supporting volume pressure.

Compactness (α)	Solar energy density (β)	Natural surveillance (γ)	Diversity of heights (δ)	Spaciousness (ε)
0,014 m^2/m^3	485,86 kWh/m^2y	10,62 points	0,13	0,025 m^2/m^2

Tab. 22. Absolute variation ranges calculated considering *maximum* and *minimum* indicator values over *starting*, *optimized* and *fine-tuned* scenarios (source: author).

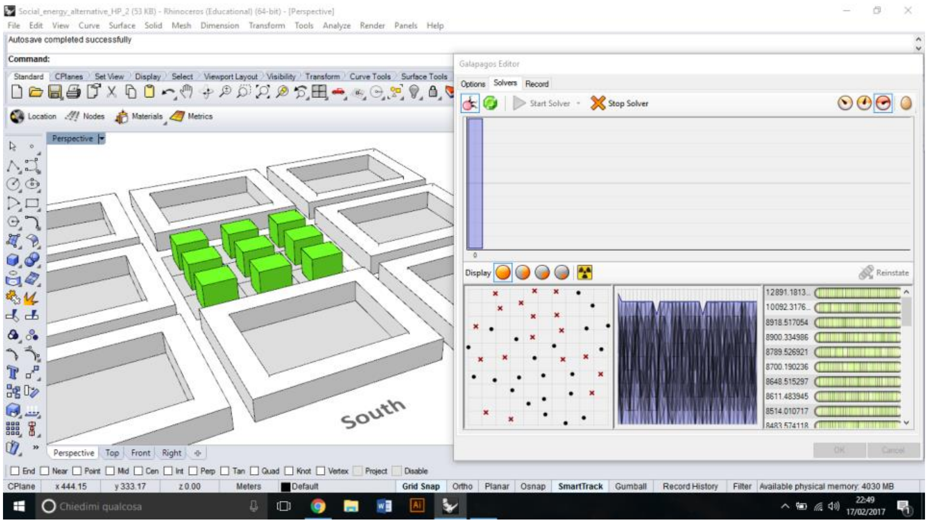

Fig. 126. Screenshot showing the beginning of the optimization process (cycle of generation number 0); we see *Galapagos* window (foreground) and the built environment in Rhinoceros, corresponding to our starting scenario (background) (source: author).

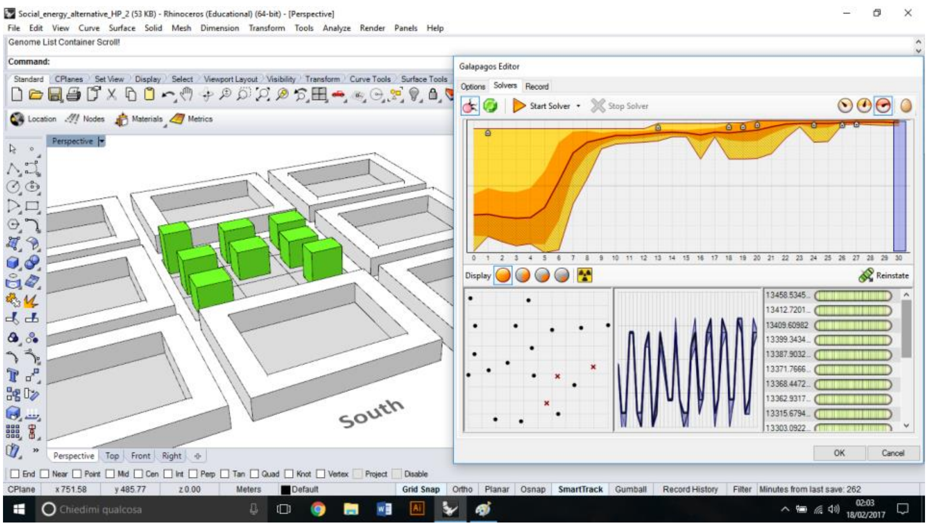

Fig. 127. Screenshot showing the beginning of the optimization process (cycle of generation number 30); we see *Galapagos* window (foreground) and the built environment in Rhinoceros, corresponding to the optimized scenario (background (source: author).

Starting arrangement (*isotropic setting*)

Our starting arrangement consists in an arbitrary instance describing a uniform occupation. Horizontally, all units take over the center of parcels with a 60% of obstruction in both *X* and *Y* directions. Vertically, plot ratio amounts to 7.5 m^3/m^2, the median level between 5 (minimum) and 10 (maximum), in order to appreciate its spontaneous tension toward one of the two extremes. Both optimization and tuning improvements refer to this layout as their benchmark.

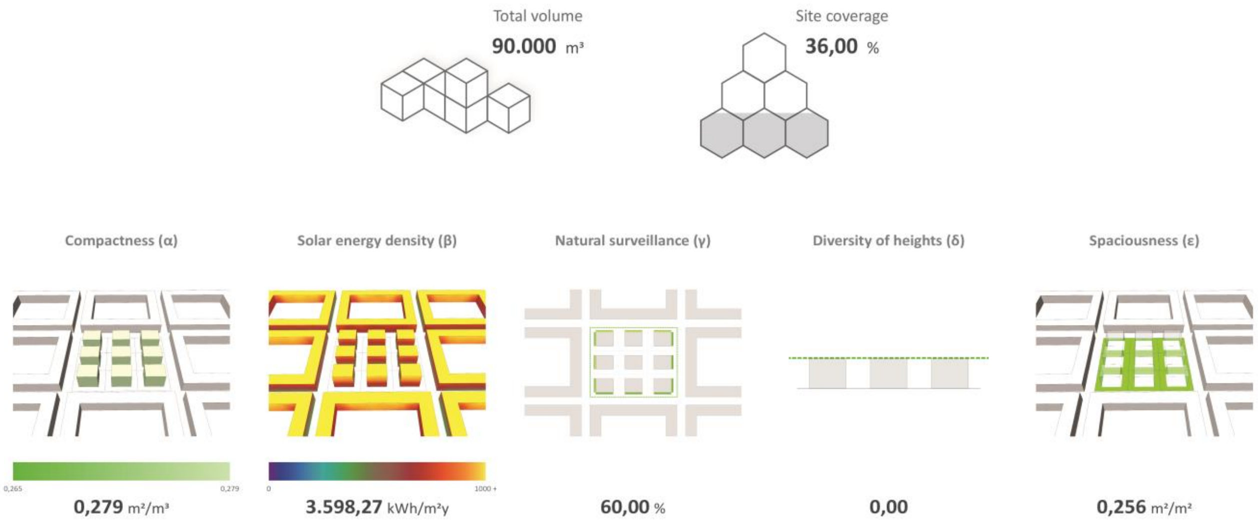

Fig. 128. The performative profiles of our *starting* arrangement and relative 3D previews (source: author).

Optimized arrangement after 30 cycles (*inverse design*)

With *Galapagos*, we considered maximizing a custom *fitness* putting solar gain in contact with heat loss propensity, the latter being represented by a measure of building compactness. The ratio between mean *solar density* and mean *compactness* of the plot has been a dodge for achieving the *optimum* with a double-sided benefit: approaching the maximum would push for augmenting solar capture while reducing the dispersion of envelop, which, in turn, would force volume growth with minor outlay of envelop surface.

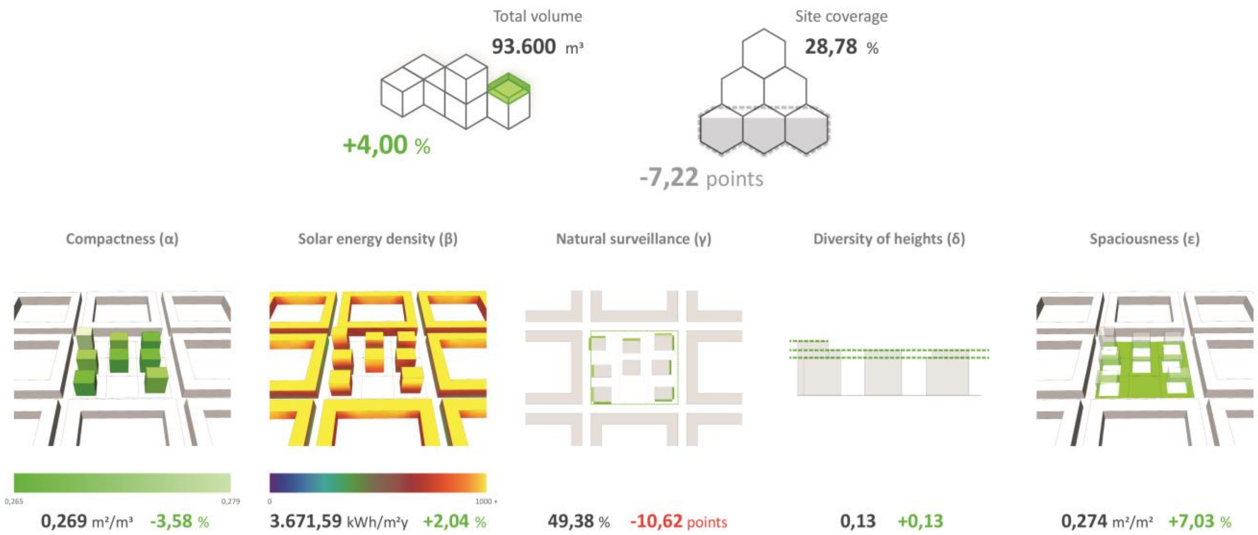

Fig. 129. The performative profiles of the *optimized* arrangement and relative 3D previews (source: author).

Cumulatively tuned arrangement (*forward design*)

Starting from the result of optimization, we opted for adjusting the design through fine-tuning, with an attention to other factors that typically press and distort occupation of space: street surveillance, height diversity and open space compression. The exercise ended up with a slighter improvement of solar capture, but dampening the loss of street surveillance while supporting a certain degree of diversity. The model currently lacks a *weighting system*, which could be further implemented with the integrated use of mathematical components.

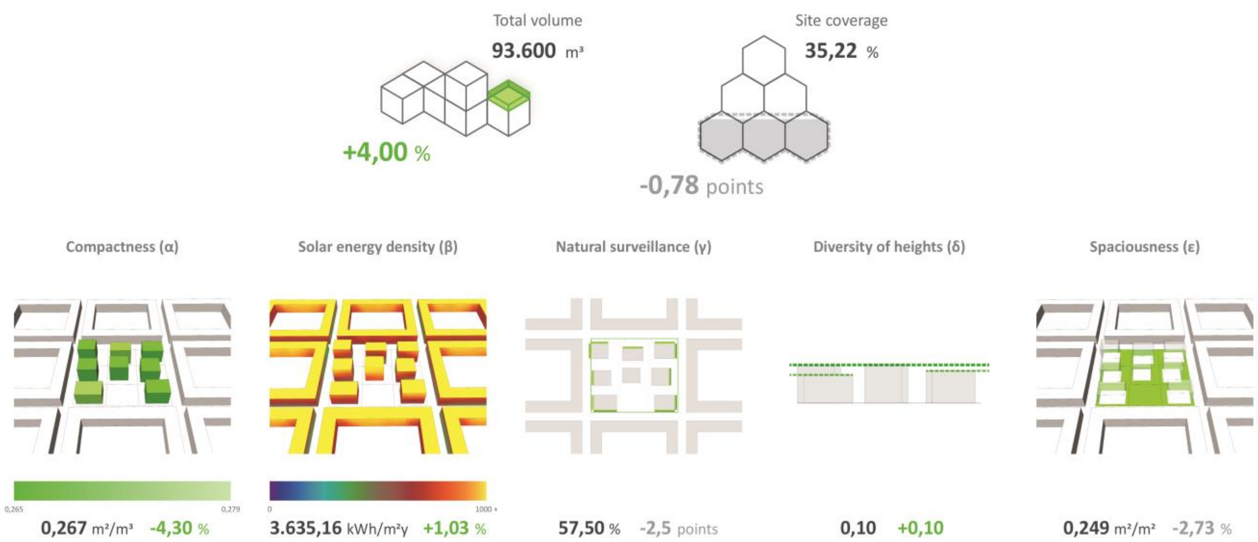

Fig. 130. The performative profiles of our *fine-tuned* arrangement and relative 3D previews (source: author).

	Absolute values		Standardized values		Normalized values	
Starting	**Compactness**	**Energy density**	**Compactness**	**Energy density**	**Compactness**	**Energy density**
0	0,279	3712,56	1,137	0,684	0,000	0,535
1	0,279	3556,55	1,137	-0,667	0,000	0,214
2	0,279	3611,54	1,137	-0,191	0,000	0,327
3	0,279	3634,88	1,137	0,012	0,000	0,375
4	0,279	3468,17	1,137	-1,432	0,000	0,032
5	0,279	3494,96	1,137	-1,200	0,000	0,087
6	0,279	3728,59	1,137	0,823	0,000	0,568
7	0,279	3558,11	1,137	-0,653	0,000	0,217
8	0,279	3619,04	1,137	-0,126	0,000	0,342
Optimized	**Compactness**	**Energy density**	**Compactness**	**Energy density**	**Compactness**	**Energy density**
0	0,265	3812,61	-1,137	1,551	1,000	0,741
1	0,271	3632,13	-0,162	-0,012	0,571	0,369
2	0,277	3749,8	0,812	1,007	0,143	0,612
3						
4	0,265	3595,85	-1,137	-0,326	1,000	0,295
5	0,272	3465,7	0,000	-1,454	0,500	0,027
6	0,272	3938,26	0,000	2,640	0,500	1,000
7	0,265	3590,58	-1,137	-0,372	1,000	0,284
8	0,265	3587,81	-1,137	-0,396	1,000	0,278
Fine-tuned	**Compactness**	**Energy density**	**Compactness**	**Energy density**	**Compactness**	**Energy density**
0	0,272	3739,09	0,000	0,914	0,500	0,590
1	0,265	3656,12	-1,137	0,196	1,000	0,419
2	0,265	3598,87	-1,137	-0,300	1,000	0,301
3						
4	0,265	3687,91	-1,137	0,471	1,000	0,484
5	0,271	3452,8	-0,162	-1,566	0,571	0,000
6	0,267	3775,89	-0,812	1,233	0,857	0,666
7	0,265	3598,89	-1,137	-0,300	1,000	0,301
8	0,267	3571,7	-0,812	-0,536	0,857	0,245

Average		Minimum	
0,272	3633,54	1,137	-1,566
Standard deviation		**Maximum**	
0,006	115,45	-1,137	2,640

Tab. 23. Summary table of solar density and compactness values in their absolute, standardized and normalized form, calculated for the insight on individual units (source: author).

Our three block schemes have been evaluated at the level of single units as well. A comparative view of optimization and fine-tuning on the energy performance of buildings required sorting disaggregated data about solar gains and compactness, and projecting them on a common scale. Data referred to every unit have been standardized as *z*-values first, and then normalized to a 0-1. We have carried out the two treatments separately, due to highly different orders of magnitude between values of compactness and values of energy density.

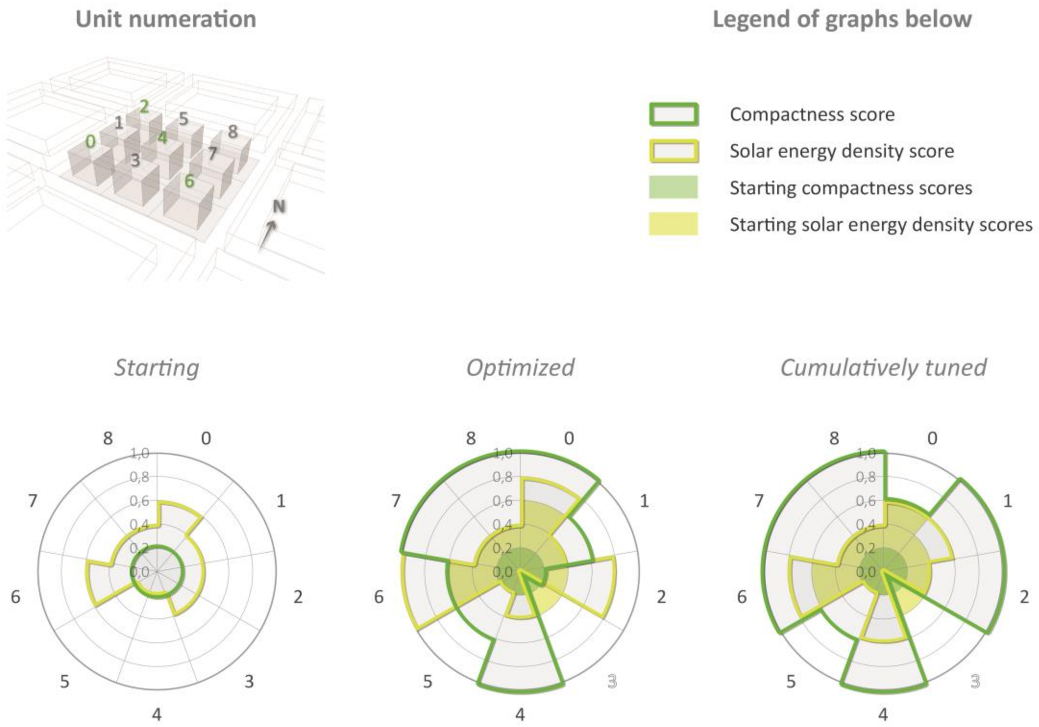

Fig. 131. Graph representation of normalized scores for the three scenarios in terms of individual compactness and solar density. Keep into account that the two scores have been standardized and normalized separately, due to sharp distinction in scale factor. Unit 3 corresponds to the building culled by optimization; all the others represent improvements compared to starting scenario. *Fine-tuning* put into effect lateral forces of occupation, yielding asymmetric (source: author).

As additional representations for individual units, we propose the contribution of single heights to the general level of height diversity (δ), and the disaggregate view of radiation density (β) for every building face. We could consider even computing variations per single faces for a full outlook, but since absolute ranges ended up with being so scant (*tab.* X), we opted for the general picture of variations per unit. The incidence of single units on the overall degree of diversity (θ) has been defined as the quota of deviation they brought in the distribution of building heights. In analytical terms, this concept assumed the following expression:

$$\theta = \frac{(\bar{h} - h_i)^2}{\sum_i^n (\bar{h} - h_i)^2}$$

Where h_i is the height [m] of building unit *i*, $\overline{h}$ is the average height [m] of units and *n* is the pure number of generated units. The proportion has been multiplied times 100 to get the equivalent percentage values [%]. An important property of this simple measure is the internalization of orders of magnitude: every deviation could be confronted with the total deviation of its own distribution, eliding the influence of average values and making it possible to compare quotas related to the same unit across the three scenarios. The insights below represent the selection of four significant units in terms of solid-void qualities and energy implications.

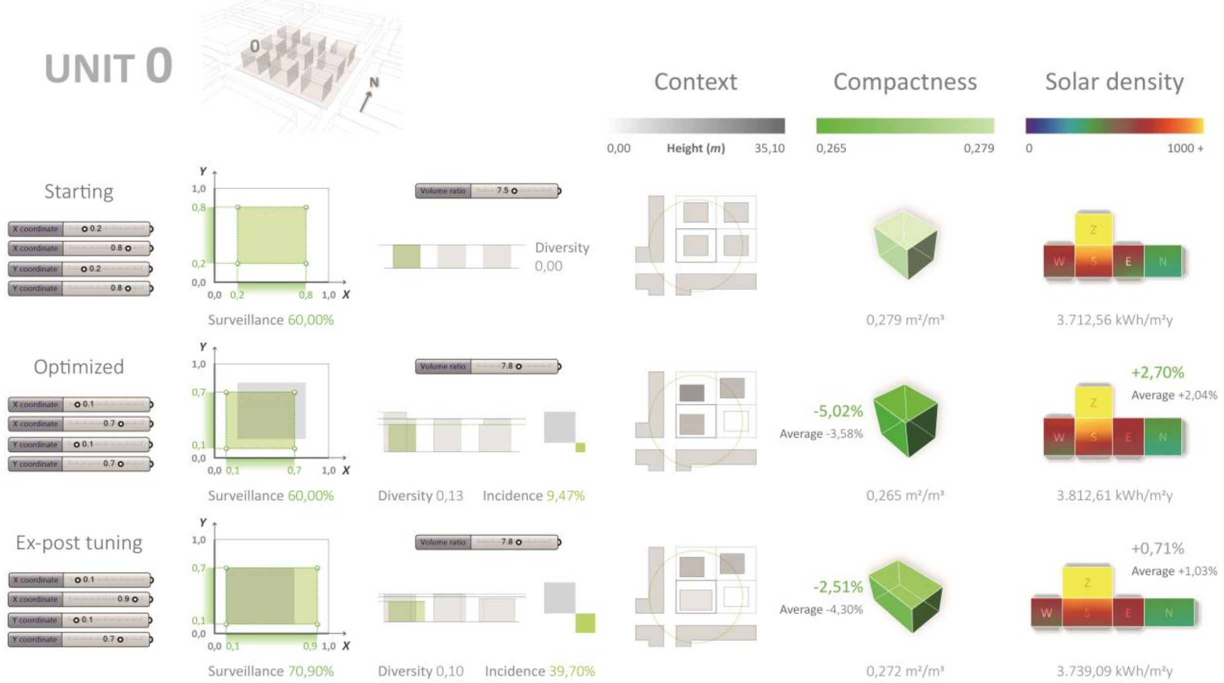

Fig. 132. Focus on unit 0 – Excerpts of horizontal and vertical parameters of occupation and respective effects on street surveillance, incidence on global diversity, pattern of nearby obstructions, individual compactness and solar density (source: author).

In the case of unit 0, *optimization* raised volume portion and compactness at the same time, with no substantial change in terms of footprint. We observed, rather, a simple "skid" toward site border. While the local increase of compactness has been higher than the average, the solar dimension portrayed an improvement in line with the general picture. The generative process comprehended the need of culling at least one unit of the neighborhood to yield some benefit for the nearest façades. In particular, this made the East portion of envelop turn entirely red. Introducing demand of horizontal occupation for the sake of surveillance has been a major concern for this unit during the *ex-post tuning* phase. Also, it is interesting to note the huge boost to incidence on diversity, from 10 to 40%, due to the much lower height compared to other units. This aspect has confirmed the conflicting nature of our distortion factors with energy performances: both improvements of compactness and solar density have been lower, compared not only to the optimum, but also to average values of the scenario of reference.

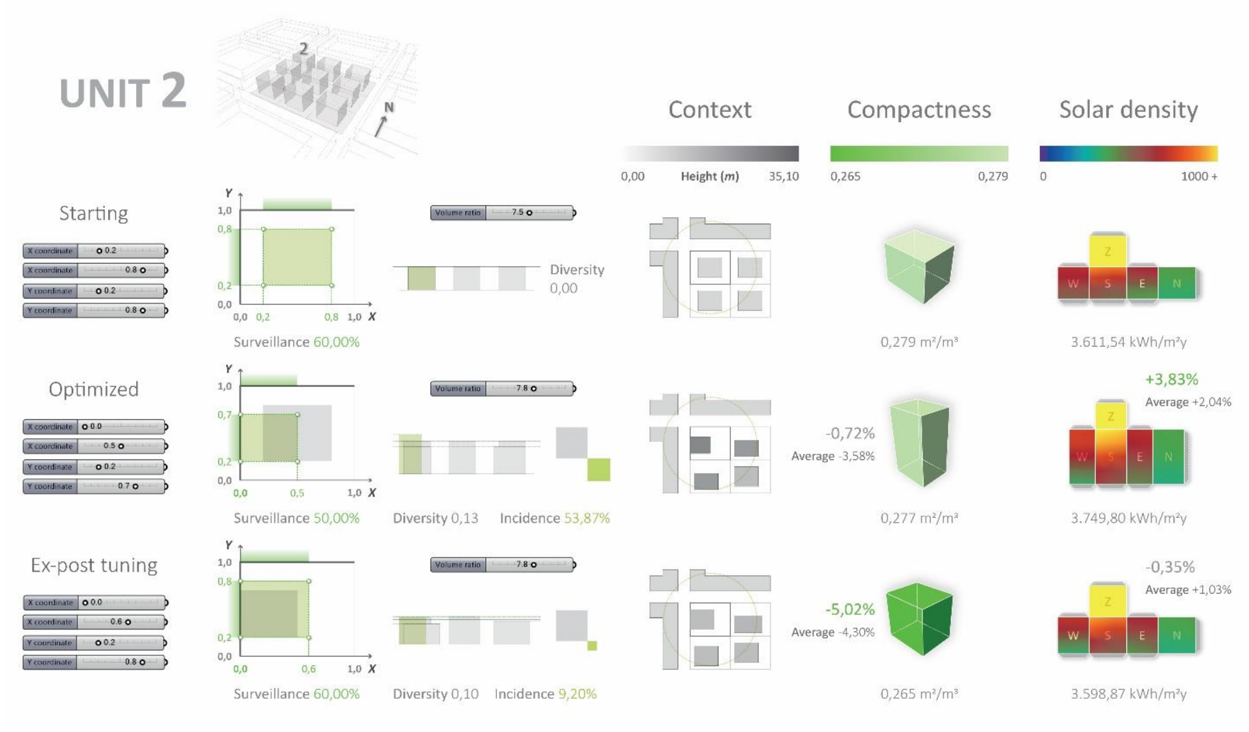

Fig. 133. Focus on unit 2 – Excerpts of horizontal and vertical parameters of occupation and respective effects on street surveillance, incidence on global diversity, pattern of nearby obstructions, individual compactness and solar density (source: author).

In the case of unit 2, we noticed a clear example of how *optimization* insisting on the whole block differed, to some extent, from the local treatment of units. In particular, the process seems to have sacrificed individual compactness for the sake of higher solar capture, forcing the growth of building height to overcome the obstruction to South-facing envelop. This tension to vertical "supremacy" over surroundings led to a slightly higher increase of energy density compared to block average. The figure for compactness is radically different, with a relatively unchanged dispersion of envelop system in spite of the general improvement. In a sense, the general payoff proved to be not negative either, if we consider that final form has kept up quite well with the mismatch between volume rise and horizontal shrinkage. Collateral impacts have been observed for both surveillance and incidence on diversity. The former showed a substantial decrease, despite the (involuntary) approach to the street; the latter had a major influence on built environmental variety. The *ex-post tuning* practice had a role in re-establishing at least the original surveillance while keeping the same volume; this reduced the individual contribution to diversity, but preserved a respectable influence. Lower height resulted in much sharper compaction, but the overall homogenization of surroundings seems to have restored the obstructions to sunlight, with a narrow, but symptomatic deficit for solar density.

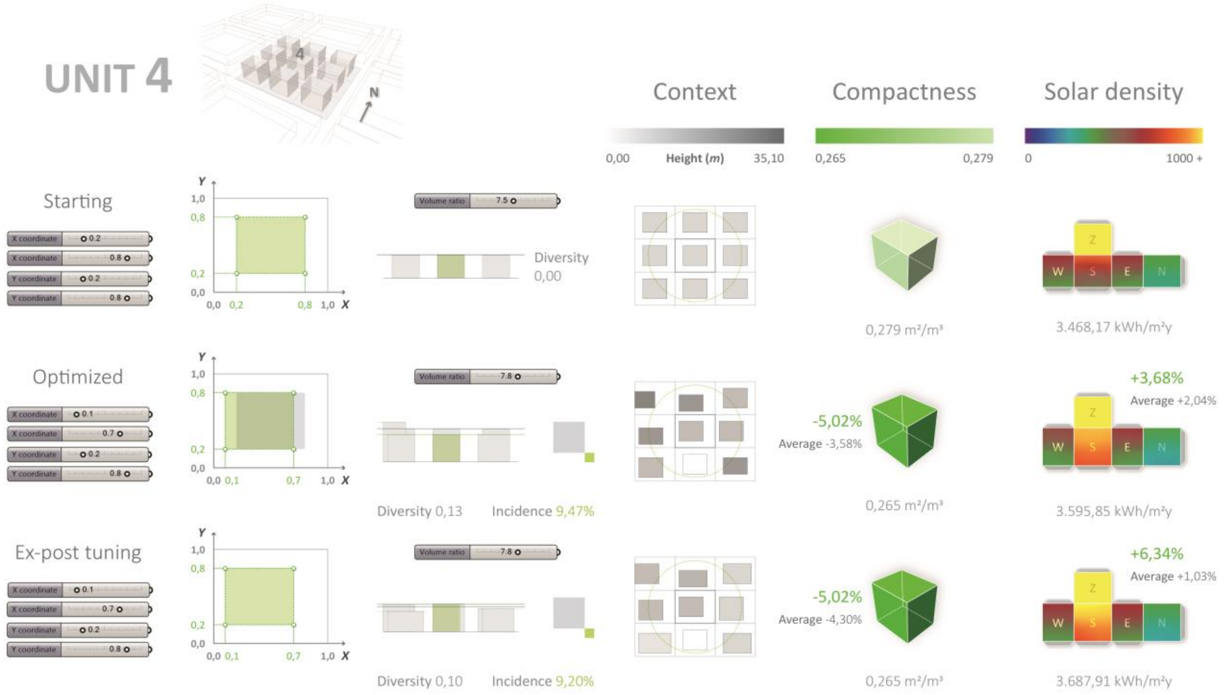

Fig. 134. Focus on unit 4 – Excerpts of horizontal and vertical parameters of occupation and respective effects on street surveillance, incidence on global diversity, pattern of nearby obstructions, individual compactness and solar density (source: author).

In the case of unit 4, the close bond between surrounding obstructions and energy implications has prevailed over the importance of both surveillance and incidence on diversity. This was mainly due to the central location of the unit, which led to dump any hypothesis of change if not strictly concerned with energy and obstruction patterns. Interestingly, the invariance of building footprint and the parallel increase of volume have flown into a combination favorable to compactness, yielding a higher benefit at the individual level. Generative *optimization* "understood" the burden of initial obstructions and reformulated the pattern to boost solar density over building shell as much as possible. In this sense, moving the unit from the center and culling the Southern neighbor helped improve the overall level of solar access, and this was particularly evident from the brightening tones of South-facing portions of envelop. Unit 4 also served to point out that refining local conditions would be possible even based on restructuring solid-void systems of surrounding environment, with no essential need to change the building in question. *Ex-post tuning* has left this unit untouched, but neighborhood conditions, while reducing the general level of energy performance, revealed some indulgence more in granting sunlight access to its envelop structure. The increase of solar density almost doubled the one registered after optimization (6% compared to 3-4%). The deviation from average value is also quite remarkable (6% compared to an average improvement of only 1%). This freedom in variating the surrounding neighborhood reflected the inherent benefit of factoring *specific quality* and higher complexity in the matrix.

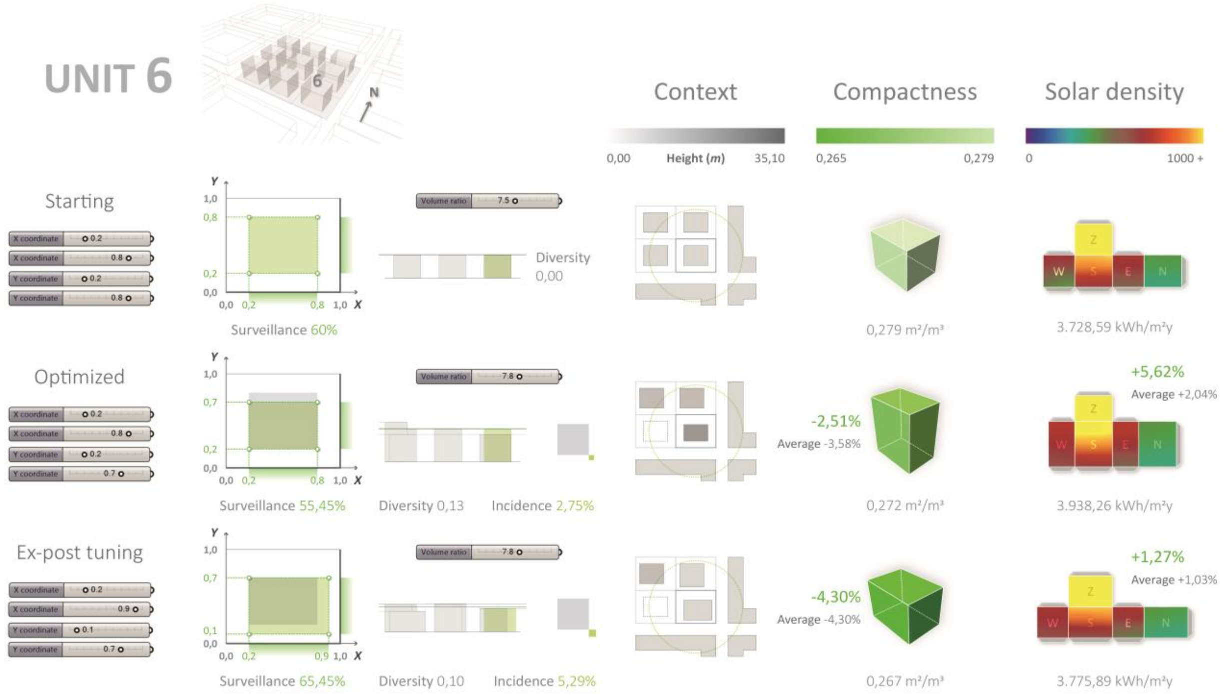

Fig. 135. Focus on unit 6 – Excerpts of horizontal and vertical parameters of occupation and respective effects on street surveillance, incidence on global diversity, pattern of nearby obstructions, individual compactness and solar density (source: author).

In the case of unit 6, the general payoff following optimization and fine-tuning practices has been quite “benevolent” in harmonizing solid-void quality and energy aspects, at least considering comparisons with block values. The *optimization* process coupled the slight decrease of coverage with the increase of volume ratio, which raised tallness to prevail over the obstructions of the context. This has been decisive for boosting energy density over most part of the envelop system. At the same time, culling the volume on the West side helped harvest radiation even more, reddening the corresponding portion of the building shell. The combination of these two benefits made evident why the variation was above the average (almost 6% compared to the 2% of the block as a whole). Conversely, compaction has been slightly lower compared to block image, but the *fitness* proved to bear fruit in matching the rise of building height with the compensation of a higher volume, thus discouraging the dispersion of envelop while still relaxing obstructions to sunlight. While being influential for both solar density and compactness, picking such instance of occupation had minor effects on both horizontal surveillance and vertical incidence, as we could spot no significant bonus nor malus elements. In particular, the unit was far from being a driver of diversity, meaning that the increase in tallness played more as a seemingly paradoxical force toward conformity. The overall demand for surveillance characterized *ex-post tuning* even in this case. Stretching horizontal occupation toward street corner served to restore and even raise the original value by at least 5 points. Keeping the volume constant, the new pattern of occupation propagated to lower height in a way that the building acquired somewhat higher influence on diversity. In parallel, the same property had divergent impacts on energy dimensions. Compactness took advantage from it, doubling the “retention” of envelop seen in the optimal scenario; the value also matched the average at block level. Such behavior could be noticed for energy density as well, but here, the increment has been leveled down from 6% of the optimum to only 1%, due to the ample reinstatement of initial obstructions.

3.4.2. Discussing the elements of inertia surging from an upright climb to morphological complexity: *front-loading*, *degrees of freedom* and the *discidium generic-specific quality*

3.4.2.1. *A first problem with complexity: the steepness of learning curve for parametric alphabet and the dramatization of front-loading, given the directed nature of diagrams*

We can first observe two conflating inertias: on the one hand, we have a time-requiring learning curve for hard skills to accomplish straightforward technical procedures, alterations of parameters and diagrammatic modifications; on the other, we need to cope with the careful management and anticipation of essential constraints, which implies growing cognitive investment at increasing complexities.
Advanced parametric practice may yield evident benefits when it comes to reproduce and manipulate complex systems of input roots toward diverse solutions. Nevertheless, the methodology requires consistent investment in both maintenance and skills on behalf of the user. This magnitude of effort is not always available in small or more generalized settings, such as small consultancies, municipal planning offices, let alone among lay people. Steinø (2010) recognizes the impeding requirement of *hard skills* training, which could furtherly intensify the typical "vocabulary divide" between technical roles and grassroots promoters at play in a pluralistic design process:

> *«While urban design is very often a collaborative endeavor, where many different views and concerns must be negotiated among a fan of stakeholders, advanced technology and high skill requirements are likely to be a limiting factor rather than a liberating one. Therefore, it is desirable to achieve conditions where the power of a parametric approach can be implemented while still maintaining a low entry level, both economically, technologically and in terms of required skills»* (Steinø, 2010, p. 2).

The author argues that, despite the attractiveness highly sophisticated approaches adopting special mathematical operators, a "low-tech" approach pledged to accessible tools and modest skills deserves attention as well, especially when it comes to a supposedly inclusive negotiation of urban space. This is, obviously, an *ethical* and *political* problem mirroring the conflictual nature of territories, more than a merely technical difficulty (Pacchi, 2001).
Conversely, current parametric design practice falls short of alternative approaches, whose distinctive qualities would reside in slightly easier testing and modification sessions for lay users, with no room for applications of expensive technologies and extra skills in computer programming: in truth, these "musts" could even become highly prohibitive in terms of time, money and cognitive effort (Steinø, 2010; Woodbury, 2010). The collaborative potential of parametric design (Steinø et al., 2013) seems to be important in this context. However, such approaches are not abundant, at least at this juncture (Steinø, 2010). "Parametric designers" may even boast the ability to develop custom parametric objects of any scale[152]. However, if users point at reproducing sophisticated and malleable designs by parametric means, they simply cannot avoid the overhead burden of a programming language in which every part of design must be scripted with proper syntax.
With reference to this latter aspect of design, we can also consider that a number of designers encounters difficulty in integrating *algorithmic thinking* into their working paradigm. It is evident that, in spite of over thirty years of valiant attempts to teach programming in design schools, this kind of approaches requires mastering a completely upside-down "mental gymnastics" (Woodbury, 2010). Algorithmic programming does not only

[152] For example, Grasshopper allows to write personalized code in C#, .NET or VB .NET to generate a custom tool (or component) able to perform that specific function. These custom components require architects and urban designers only to know what to feed in as an input (such as curves, points, boundary representations, etc.) and what the output would be (Koltsova et al., 2013).

mean speaking a new language: a different language implies restructuring human thought toward unexplored forms, which requires time and sizeable efforts in reformulating the ontology of a creative process[153].
As these limits come to mind, it seems surprising that, in absence of highly specialized packages and technical skills, parametric potentials completely fall apart, despite claiming to overcome the rigidity of traditional masterplans. The delusion of a supposedly boundless flexibility of parametric diagrams will not cease until we keep emphasizing what parametric design can do in *theory* while overshadowing how models come to be in *practice*, which should be, actually, the real core of our reflection. Witnessing change "sliding" from one instance to the other does not restore the cognitive effort required for granting a stable and well-functioning matrix.
This cognitive effort stands for the quota of "extra-work" we need to pay to expiate a process-oriented perspective (Fraser, 2012). In other terms, we can interpret it as "the other side of the coin", where the "coin" represents the benefit we gain from probing a *continuous* and rule-based gradient of design alternatives. Transferring the focus from outcome to process hugely subverts already accustomed and well-rooted design paradigms, which, unlike parametric modeling, strictly orient usual practice to check one-off designs against a rule, more than to extract concrete alternatives out of that same, abstract rule.

> *«When you model using parametrics, you are programming following similar logic and procedural steps as you would in software programming. You first have to conceptualize what it is you are going to model in advance and its logic. This is in contrast with what generally drives human cognition; we expect form to comply with rules, but not rules to shape form as an indirect consequence»* (Smith, 2007).

While machines can implement and support procedural modeling, human elements generally rely on the figurative essence of individual designs, that is, how each of them appears and what it suggests to ocular scrutiny: this is an essential language for designers to express intuitive knowledge and creative thought.
In contrast, parametric design compels to a clash between rigid rationality of digital algorithms and boundless intuition of analog minds. "*Front-loading*" is the extra-work coming from the inevitable compromise with what the "eyes" of machine can read and interpret, based on the procedural syntax of diagrams (Davis, 2013; Fraser, 2012). As recalled by Smith (2007), generating a parametric model always entails some degree of upfront planning, for it is required to imagine the output only as a fragment surging from dismantled and systematic orders of genetic conditions. This means that patterns of thought and intuition have to articulate precise, unambiguous and highly deterministic lexicon into careful connections of input and output data, paying attention to the generative sequence of form. *Directivity* is crucial in every parametric diagram, whether this is linear or circular. Thus, anticipating the scheme of interdependencies becomes an equally crucial duty. It is always essential to plan component hierarchy with upfront logical rigor, both globally and locally, due to the extreme sensibility of input-output connections. At increasing complexities, when sets and sub-sets of components dramatize the intricacy of wires, logical rigor calls for major cognitive investment (Gerber, 2007). Weisberg (2008) states that even designers creating parametric models with *Pro/ENGINEER* in the 1990s needed to

> *«carefully plan the design, defining ahead of time which major elements would be dependent upon other elements»* (Weisberg, 2008, p. 16-12).

[153] Besides, according to Woodbury (2010), it is even less surprising that computer-aided design relegates programming to the background. Almost all current systems have a so-called scripting language. Although these are nothing more than programming languages, developers tend to label them as "*scripting languages*" in the hope to disguise a workload that could appear baleful in the susceptible eyes of architects and planners.

In essence, *directed graphs* cannot do without concepts like hierarchy and dependency, and this requires choosing a precise order, i.e. which operation should come first and which after, paying careful attention to how one sub-process of the solver could relate with the others. It follows that parametrics represent a harshly deterministic technique that always implies some sort of "*fragile rigidity*", with zero tolerance for, and great vulnerability to unfitting change.

Complexity tends to dramatize front-loading, for assemblies that are ever more intricate denote full integration and, by consequence, higher sensibility. Modifying definitions with no risk of rebuilding the diagram becomes particularly challenging (Woodbury, 2010). This trade-off between complexity and tolerance cannot but typify any attempt to untangle, through one explicit and "chained" sequence of constrictions, the inherently holistic and "out-of-the-box" essence of human thought. The essence of design as management of *product*, where constitutive elements conflate within pure *addition*. Working on the hierarchy of elements, parametrics represent the management of *process*, which implies raveling single elements based on precise orders of *association*. This totally reformulates our perspective on design change, especially if we assume change to be multiplier of complexity. Accommodating change, i.e. introducing new, and sometimes even sudden or unexpected conditions for geometry, can be problematic for both conventional and parametric approaches, but in two different ways. The formers consider probing transitions of the same concept as prohibitive, if not practically impossible; the alternative would be trying to reproduce some of the nearly infinite solutions for that concept, but, at the same time, proving actual accordance with rules for each of them would become a demanding procedure[154]. Nevertheless, embedding a new concept, or even transmuting the current one, does not necessarily represent a major endeavor. Design would still have static properties, but it would also be able to support a straightforward "paraphrase" of human intuition, because its basic elements do not have to reformulate mutual dependencies but in our mind, regardless of how intricate these are in the model. This is, by the way, the natural consequence of conflating geometries within the same level of *addition*. Conversely, *association* entails chaining elements into strictly codified relationships, placing geometries over different levels of dependency, and concurring to summative (unknown) impacts. Parameterizing result through its process of generation leads to a specular image: provided the exact translation of intuitive knowledge into unambiguous language[155], a definite concept can be explored quite flexibly, based on parametric levers. This allows for testing nearly infinite, "decimal" variations of that concept against a number of criteria. We did this through a rudimentary application, even appreciating the search of an *optimum* within the scope of our constraint system. However, we cannot be so sure of whether our matrix, as we have conceived it in terms of input and processing conditions, would easily intercept further concepts in accordance with both previous and following steps of the hierarchy. Revising the concept through newer complexifications, such as rotating buildings or irregular parcels, would imply finding the most suitable place to include them along the process, which comes at the cost of a degree of reformulation that can be more or less prohibitive, but either way proportionate to the intricacy of flows.

Codifying a "grid", that is, constraining form to a determinate behavior, has a systematic conflict with the need to fully and promptly intercept unexpected change. The evident consequence is that designers may invest time on the "wrong" approach, that is, an approach that cannot sustain truly adaptive and self-consistent properties in case of localized change (Kilian, 2006).

> «*The challenge of building a parametric model is to untangle the interdependencies created by different requirements and find a set of rules that is as simple as possible while remaining flexible enough to accommodate every occurring case. In other words: to pinpoint the view to the exact level of abstraction where no important point is lost and no one gets distracted by unnecessary detail*» (Scheurer and Stehling, 2011, p. 75, quoted in Davis, 2013, p. 41).

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[154] Think, for instance, that even verifying constancy of volume at every change of built geometries, this being either subtle or radical, may call for disproportionate effort in conventional modeling.

[155] Translation that has to deal with both coherence of data formats and a much more profound meaning of data flows.

Considering how geometrical properties may affect subsequent moments of evaluation, designers are required to *abstract* the diagram up to a certain level: a level such that it comprises all the possible changes one may ever imagine for that rule. In other words:

> *«to avoid unnecessarily rebuilding the model by anticipating future changes and creating parametric models with the flexibility to accommodate these anticipated changes from the start»* (Davis, 2013, p. 41).

3.4.2.2. *A second problem with complexity: the importance of neutralizing spurring degrees of freedom through proper dimensioning of constraint load within the system*

Within a context of increasing complexity, the management of abstraction falls short in sizing constraint intensity promptly, which leads to additional cognitive investments from a designerly point of view. We observed a difficulty in translating our intuitive knowledge through hierarchic and procedural grammars that seem not to permit any tolerance in terms of inbound (left) and outbound (right) information flows (Fraser, 2012; Zarei, 2012). Instead, this second and parallel problem consists in making seemingly "obvious" rules explicit enough to prevent prospective violations. The burden of diagramming form compels designers to not only identify and place the "right" component at the "right" moment, but also check whether it is needed or not to further constrain the generative matrix with extra components. The very notion of *constraint* intertwines with the concept of *degrees of freedom* (Anders, 2003; Burry, 2006; Monedero, 2000), which is extremely relevant for well-functioning generativity.
Parametric diagrams are solvers called to abstract (or generalize) forms based on the government of topological properties, which depend on a certain number (*n*) of independent variables, and a certain number (*m*) of (geometric, logical, mathematical) conditions. Both describe the overall system of constraints. Degrees of freedom stand for the "depth" of such system (Fraser, 2012, p. 23), that is, the scope of circumstances that an algorithmic definition may spawn across the computation process. This "depth" varies according to the amount of variables and the intricacy of processing operations, which means that it is directly proportional to the complexity of the design problem. Hence, we can consider implanting and removing constraints as measures for governing degrees of freedom, filtering what, according to our rule, should not belong to the solution space. In other words, each constraint serves to diminish one step the alternatives we can extract from the gradient (Monedero, 2000).
Determining the exact number and type of constraints in respect to a generative rule is not an immediate task. Complying with that rule implies a thorny balance between *under-constraining* and *over-constraining* the matrix. If we under-constrain the diagram, we cannot expect the matrix to be consistent with our rule, because it still requires specifying missing conditions, such as some extra operation to be correlated, in turn, with existing or new parameters. In the worst case, the matrix would not even return any visible instance, due to the absence of critical information. Conversely, if we over-constrain the diagram, design problem cannot be solved either, because that implies falling most likely into recursive statements that spawn contradiction somewhere (Fraser, 2012). Therefore, it is evident that abstraction should drift apart from the two extremes, granting neither more nor fewer constraints than the ones necessary for that rule. Achieving the proper number of constraints corresponds to zeroing the degrees of freedom of the system, reaching the equilibrium point where intuitive conditions converge with a requisite of full determinacy. Diagrams that reduce degrees of freedom to zero automatically exclude violations of the rule from their solution space, which makes them consistent and efficient solvers (Fraser, 2012; Monedero, 2000).
As we complexify conditions, the fine line between under-, properly and over-constrained systems fades away proportionately. *Error* and *warning statuses* like *Grasshopper*'s inform users of either wrong or inadequate data, but the tasks of locating the fault, reformulating definition and calibrating constraint load are always on behalf of the designer, who is also responsible for the local and global sense of flows. Plus, diagrams displaying *correct statuses* do not necessarily nullify their degrees of freedom, because these pertain to the intuitive meaning and

purpose of conditions and not (only) to the basic compliance of data formats. As such, they represent a further nuance of constraint systems, which may assume subtle, and sometimes even undetectable behavior.
Among the series of failures surging from the practical, rather than theoretical dimension of parametrics, Davis (2013, p. 44) and Smith (2007, p. 2) consider "*change blindness*" to be as more influential as we introduce more and more intricate textures of associations. The authors refer to inadvertent changes of parameters and conditions that, while not conforming to intended rules, risk going unnoticed however visible they may be on screen. Yet, the trouble with locating flaws in how not properly change, not even coherence of format, but the *sense* of constraint systems converts human intuition works the same way: complex forms, like the *urban* ones, require paying attention proportionate to that level of complexity, at least the one we expect to manage.
This further "*blindness*" amounts to the problems of managing complexity of forms along both a steep learning curve and a challenging control of procedural, propagation-based syntax. In particular, the "*fragile rigidity*" of a parametric matrix makes it particularly sensitive even to what can be seen as a minor fallacy, because responsive or autopoietic systems *propagate* errors in much the same way they propagate correct information. Hence, extensive trialing and validation, which can be as more onerous as we complexify conditions, becomes of primary importance if we do not intend to interlace "blindness" with the "dark side" of propagation.

> *«You then program, debug and test all the possible ramifications where the parametric program might fail. In doing so, you may over constrain or find that you need to adjust the program or begin programming all over again because you have taken the wrong approach»* (Smith, 2007).

3.4.2.3. *A third problem with complexity: the cost of dumping generic quality with specific quality, from contraction to explosion of data flows and computing strain*

The achievement of *specific qualities* represents, in our case, the complete freedom in controlling bulks as independent structures. This feature of the system is intended to sustain numerous and diversified patterns as a generative consequence of bottom-up (re)organization. As such, it requires multiplying the "*depth*" of the matrix, by definition of an exact correspondence between number of parameters and number of dimensions considered (Zarei, 2012). This, however, also has implications for computing strain, especially if we attempt to run a certain number of optimization cycles involving, in turn, a certain amount of genes and random generations. This is a non-banal aspect of parametrics, because the performance of technology support in solving a problem is indirectly proportional to the complexity of that problem. Hence, calibrating parametric dimensions with a careful reduction of complexity becomes an important compromise for actual feasibility. In effect, we did this in our model, assigning multiple settings to horizontal occupation and only one parameter for vertical counterpart. Considering the experiment of optimization to come, unleashing specific qualities for both horizontal and vertical profiles would have slowed down the whole calculation (and simulation) of outcomes.
Other than being non-banal, resistance to "depth" is not new. Confrontation with novel challenges has been a constant of parametric history, an aspect parallel to the increasing sophistication of tools. For example, a similar problem concerned users of *Pro/ENGINEER*. Diagrams normally began to abate performance once dealing with assemblies that spurred from wide-ranging combinations of *individual* parts.

> *«These models could take a considerable amount of time to load (retrieve from disk memory and prepare for interactive manipulation) and to regenerate when changes were made. Faster computer systems helped but users were starting to build increasingly complex models. Model size was increasing faster than the speed of the newest computers could handle»* (Weisberg, 2008, p. 16-12).

Although this friction seems to depend on pure computing power, the procedural genesis of parametric models plays a likewise significant role. Working on a process, especially if we consider more and more elaborate networks of associations, entails configuring the unceasing recomputation of outcomes at each "decimal" change of parameters, precisely because a process does not end up with reproducing independent signs, but, rather, it governs a self-consistent and embedded behavior of form (Barrios, 2014; Tedeschi, 2014). This suggests that if designers point to experiment the effects of particular rules on form with a constraint system, they need to size the problem to be solved according to available technology, without too much sacrifice for complexity assumed originally through intuition. Accomplishing control of complex systems as the built environment implies that users should find reasonable allocations of generic and specific qualities across the matrix. In short, reasonable allocations of *degrees of freedom*.

Therefore, the notions of constraints and *degrees of freedom* also relate to an influential trade-off between ease of management and risk of perpetrating *generic qualities*, which stem from nothing more than overly simplified and reductive instructions. As with what happened in solid-void repetitions of case *B*[156], generic qualities translate to buildings with equal shapes and volumes, i.e. with the same reactive behavior to parametric change.

This comes about as we reduce the intricacy of relationships that naturally originates from complexity of design rule and, by consequence, from the rise of degrees of freedom, which shall always be nullified through proportionate textures of associations. In this case, we could opt for *contracting* data flows along the same wires, that is, processing all inputs in the same way; however, this would mean dumping the hypothesis of assigning different instructions to different items, which, conversely, would *explode* wires. Contraction happens to be useful for providing governability and computational lightness to the syntax, but at the expense of *specific qualities* of design (Steinø, 2010). Actually, introducing randomness as an input would help simulate independent behaviors for groups of geometries by means of a single parameter, but this would embed only a partial reproduction of specific qualities, because it excludes, by contrast, any correlation between intuition of change and observable behavior of single geometries.

An ancillary reflection: the trade-off between rules and exceptions, due to the associative structure of compositional outcomes and the issue with "gridding" models according to constraint systems

Following the stream of parametric drawbacks, it may be interesting to investigate the overlay degrees between approaches vowed to *automated generation* of forms and the *socio-cultural epiphany* of urban design products, which also deserves attention. Designers always need to appreciate the political implications of technical tools with reference to contextual reality (Palermo & Ponzini, 2014).

In this perspective, parametric practice may also hide a parallel *discidium* between how it sounds to amateurs and what it could represent as application spreads with enthusiastic, but unreflective thinking. In a recent essay, Steinø (2010) pinpoints the possible relapse of planning as an approach driven by standards, which would turn a newborn technique directly into an old-fashioned one. As such, the approach would likely delegate the site-specific differentiation of urban solutions merely to the "vernacular" function of private architectures, and not to the intimate configuration of urban public space, whose symbolic quality is primarily an important premise for social representation and change. Through this lens, the specter of urban landscape *banalization* (Muñoz, 2008) turns out to be closer than we expect. Some doubts about algorithmic forms of modeling, which happen to express shapes through their own *computational* lexicon, rise as we conceive the emergence of landscape as coming from a different lexicon, the one of *cultural* appropriation, expressing the osmotic membrane between humans and their environment (Gambino, 1997; Ritter, 2001). The extent to which the two lexicons converge in a parametric diagram is still far from being clear.

Aside from how ideas are converted into tangible forms through creative processes, architectural and planning choices are inherently political and cultural products. On the contrary, Steinø (2010) highlights that most applications of parametric modelling to both architecture and urban design fall into one of two strands: the first being "form for form's sake", i.e. the "platonic" contemplation of pure morphologies, and the second being the opaque negotiation of environmental concerns, masked by the supposed sophistication of technique.

[156] Section 3.2.3, dedicated to the *Complexity* layer of this research, has shown particular regard for this aspect.

Quite similarly, Tim Love (2009) defines the spectrum of parametric design purposes as a locked gradient from self-referential strategies of "gee-whiz" *form-making* to a rather facilitated emphasis on social and/or ecological concerns, with, again, trivializing effects. Besides, both extremes also seem to reflect a diffused *modus operandi* within the architectural gotha (Ponzini & Nastasi, 2011), where the typical design philosophy bypasses the need for social representation and environmental quality by capitalizing on merely iconic features. However exceptional, icons essentially remain vacuous wrappers when attention is only pledged to how shapes look like rather than how well they perform or what message they intimately express. In this sense, the controversy about parametric modeling does not reside in the use of algorithms *per se*, but rather in the sophistication of such design mode as a pretext for justifying superficial interventions.

Tim Love seems to be wisely critical of both streams, in defense of responsible design choices. On the one hand, *form-making* through parametric software may concur in masking a lack of genuine *form-making* competency: complex forms would be generated from data of inscrutable origin, which could undermine both traceability and authenticity of modeling methodologies, despite the temporal gains. On the other hand, what appears to be a concern for social and environmental quality is too often a "veil of chastity" over designs that, in the end, are merely narcissistic explorations of form, with the sole added value of automated modeling as a comfortable "magic wand" for designers. This is perhaps the most hazardous interpretation of parametric design. In one of his passages, Love suspects that this kind of approach, paired with a scarce consideration of site-specific factors, may only reproduce an "*easy complexity*", regardless of urban design as a careful craft able to grasp the unique reality of both material and immaterial contexts:

> *«It's too often the case that the process of creating forms by inputting and manipulating data does not require that the designer develop a nuanced and comprehensive design strategy; and the process itself can produce a spurious and easy complexity that masks the absence of that more expansive approach. In some projects, for instance, specific cultural, social and physical contexts are deployed mainly as tactics for autonomous form making»* (Love, 2009).

In this passage, Love depicts the delusion of a purely algorithmic world, where an *easy complexity* disguises the immovable difficulties of *design synthesis*. Every urban process, with no exception for planning composition, can be realistically understood only in relation to profound contextual factors, for truly complex systems like cities result from the simultaneous (synergic, conflictual, multi-layered, multi-effect) interaction among their local realms (Batty & Torrens, 2001). Physical contexts are different and unique because they mirror different and unique identities.

Instead, the language of algorithms, although unambiguous, shapes and reshapes urban environments with its own syntax as a fixed format of genetic rules, independently from how cultural identities give form to peculiar contexts over time. This relevant *trade-off* between rule and exception can be an obstructing paradox: in fact, it directly interferes with *associative dynamics*, a fundamental feature we find at the core of parametric modeling (Steinø, 2010). A parametric model can be controlled in every detail by leveraging the encoded relationships among its constitutive parts. However, as soon as these parts become *unique*, the power of a parametric system is lost. In *real complexity*, something that responsible urban design captures through constant learning, design solutions end up departing from the *generic quality* of algorithmic arrangements of space (Steinø, 2010). This happens to different extents at some point of a *synthetic* process, but still it is a likely evolution pattern in urban design practice. Parametric control, notwithstanding the real-time updates and *propagation effects* that could depart from every input of the system, keeps up with the creative logics of *design synthesis* only until a certain point of this process, where algorithms are still helpful in filtering generic spatial qualities without narrowing too much the room for original solutions[157].

As we have already said, this *trade-off* is deeply rooted in the algorithmic vessels that typically govern morphogenesis in parametric design (Woodbury, 2010). We know that, unlike conventional modelling, a parametric

[157] Until the late stages of design are not reserved for advanced applications; subsection 3.4.2.3 will strictly attach to this latter point by pointing out a parallel (and likewise critical) trade-off.

system endorses the use of scripting languages to make designs. These languages provide a *binding function* that can add, modify or erase objects in the model, while travelling along the *associative* binaries of its specific constraint expressions. This means that parametric systems bring the supposedly irksome mathematical world of algorithms closer to the more accessible design models with a sort of figurative attempt. In addition, they do this by localizing algorithms in a set of hierarchic nodes, whose interactions innervate a malleable, combinatorial graph.

However, designers still need to skillfully grasp algorithmic thought, if they want to obtain the most out of such systems. The use of every scripting language, no matter how difficult, compels to flip over natural and heuristic thought, rejecting pictorial, interactive representations that have long been the unbeaten fertilizers for inventiveness and creativity in *design synthesis*. The inherent effort in reframing accustomed paradigms of thinking toward "upside-down" programming logics should not be underestimated, for human rationality is arguably a primary determinant of design quality. Besides, combined with this latter aspect, the conversion to *scripting* as an activity based on a predefined set of parameters that, in turn, call for highly specialized users, tends to raise issues of *representativeness* with respect to the social and political interests at play in decision-making. In this framework, the levels of representativeness, which concern both choice and construction of parameters, do acquire importance as soon as we consider the adherence to contextual desires as guarantor of a meaningful and unique local identity for new developments. More specifically, we should note that, if we deal with symbolic, suggestive and metaphorical expressions of urban future on one side, a parametric approach leads us to the translation of "warm" and evocative images into a much "colder" scripting system of rules on the opposite side. The possible loss of information between these two modes of expressing design intents refer to a more general reflection about thought and language relationships, which is, clearly, not simply a planning problem, but a philosophy of mind *quaestio*.

Contrarily to figurative suggestions, parametric designers have to work in a domain where algorithmic instructions are ultimately textual, however catchy the dress of data connections, control levers and informative windows may be in a *visual editor*. It follows that parametric novices need to pick up a new alphabet if they point at fluently mastering, understanding and interpreting a parametric diagram, especially when it comes to complex systems of relationships. This is not so surprising, as we recognize that *algorithmic thinking*, despite its visual translation in *node diagrams*, contrasts with almost all other forms of thought. The sheer distance between representations familiar to designers and those needed for algorithms exacerbates the gap (Woodbury, 2010).

These aspects are not only a matter of workflow patterns: they involve the "genuineness" of outcomes too. In fact, non-algorithmic forms of thought comprise the influential ability to investigate and interpret spatial qualities in novel and ingenious ways, with no particular boundaries to the imagination of interesting conceptual strategies, aside from individual talent, knowledge and experience. What happens next is the intrinsically *additive dynamic* of assembling and questioning *discrete* scenarios over time. On the other side, we find an almost specular image, leading to outcomes of likely different class. Automated forms arise through algorithmic algebra, with its virtuous mathematics and logical relationships. At the same time, the *associative dynamics* of such algebra outline predefined grids where forms, despite traveling toward *continuous* scenarios, linger within precise liminal boundaries. This is, essentially, the crucial break line between our two approaches: while we know (and trust) creative thinking and its heuristic, "out-of-the-box" power (Albrechts, 2005), we completely ignore how a pre-packaged algebra of algorithms, with codified terms and conditions, lexicon and grammar, would reproduce the schemes of such power by valuing the exploration of unique, site-specific distortions to the grid.

3.2.5. Some hypothetical perspectives of research linked to the *associative* benefits of the tool: exploring further constraints and evaluative dimensions for spatial occupation

The problems and restraints we have encountered, respectively, in specialized literature and in our rudimental application are congenital features of a methodology born for spaces of action that, compared to urban design domains, are limited in scope and complexity. Managing the behavior of much more composite forms, like the urban ones, with the simple transposition of the same toolkit may have been a chancy try. Yet, limiting research to the power of pure geometry, while recognizing specialisms going beyond architecture and engineering, led us to imagine and experiment what parametrics can do for the organization of elements related to urban composition.

In particular, aside from the content of results, this perspective has been useful to capture at least the flavor of using parametrics within a context of complexification, which pushed us to acquire some critical consciousness about the frictions coming from such premise. Given that these problems, however critical for design thinking, pertain almost exclusively to technical dimensions, we can assume the chance to overcome frictions of practice with the further sophistication of tools, which may supply components and functions ever more explicitly oriented to city systems (Galli, 2014). This is nothing more than a linear projection of parametric history. Increasing levels of *intuitiveness* in scripting, together with the lively contribution of programmers, may be drivers for ever higher popularity among lay users. The *abstraction* enabled by *digital* procedures of parametric modeling has been and will be central to this concern. Vanguards of the last century, such as Frei Otto's experiences with material computation (2003), traced a cultural revolution that, finding fertile ground in digital technology, has magnified the intelligent behavior of form toward versatile conceptions of evolution-based and self-organized mechanisms. These conceptions could only be grounded on the natural parallelism between scripting and genetics: just as genetic engineering "rewrites" the inborn behavior of organic matter, *digital* computation, unlike its *material* counterpart, would become the key to reproduce any condition of performance, including the ones we may ever relate to the urban dimension.

Parametrics interpret final form as the unknown variable of the equation. This novel perspective reformulates the search of "good" or virtuous morphology into the design of "intelligent rules" (Fusero et al., 2013), which has strong affinity with the role of planning schemes, for these assume the management of form through setting conditions of performance. Hence, the approach shows some predisposition to a framework that is not explicitly focused on the materialization of operational, *concrete* projects, but, rather, on the inspiration of adaptable (*abstract*) principles, which shall be conceived for a range of diverse, but desirable developments. In this sense, incorporating parametric software into urban design may be an interesting strategy, not simply for a matter of automated representation of objects[158], but even for the process of generation of masterplans. Masterplanning may draw tangible benefit from the real-time simulation of parametric forms, particularly in comparison with the observed state of the art. Through the combined use of custom definitions and nebulas of specialized components, parametrics may perform not much as *The* model for development, but more as an auxiliary tool for planners to envision and question diversified hypotheses. This prospect would consist in some sort of interactive platform, where decision upon spatial occupation, based on sifting "what if" scenarios, is informed in the making (cf. Schön, 1983).

[158] Which proves to be helpful, of course, to the direct perception of what a neighborhood would look like after the implementation of specific changes.

A vision for *parametric urban design* may instrument the design of masterplans with active feedbacks on space occupation and land-use efficiency. In this respect, we can imagine it a tool for appraising the possible formal implications of planning choices, which would inform the negotiation of density indices based on the intersection with guideline criteria.

Reproducing a correlation between shape and density elements, this tool could assist designer in probing that space between plan and project where decisions upon plafonds and design codes have massive implications for sustainable development. In particular, this would help (re)formulate spatial planning and urban design decision in accordance with on-site energy impacts, starting directly from district scales. For instance, translating an extensive regulation proposal into part of a constraint system could enable the assessment of energy behavior across the alternatives based on that regulation. In turn, information drawn from results could even inspire amendments to the rule, helping prevent possible conflicts with standards of performance. Designers may also consider applying the same approach to the evaluation of small-scale infills within consolidate fabrics.

Within this framework, imagining a field of *associative dynamics* among development forms may be useful for simulating measures and impacts of urban equalization. Parameterizing receiving areas with volume loads may provide an interesting basis for tuning quantities in coordination with available surface on one side, and various typological options on the other. Most probably, this prospect would be grounded on generic qualities, i.e. bulks assuming equal behavior in terms of outline and volume portion. Despite the approximation, designers could draw at least some broad hint about critical thresholds of development: this hypothesis stands to reason in case of planning schemes where quantitative pressure of private volume triggers a disproportion of executive standards. In this sense, a parametric coordination between densities, shapes, standard and receiving areas may shift negotiation away from questionable scenarios[159]. Reformulating constraints through an appropriate definition, the same approach would also inform reward systems of special decrees, keeping under energy demands from the early design phase (cf. Nault et al., 2015). However, sophistication of diagrams through *specific qualities* would insist on diversified properties of occupation, triggering even more insightful material.

The prospect of further and sophisticated constraints may involve transformations of geometry that would be simple, yet extremely influential for energy phenomena such as solar density, as well as compactness and comfort of solid-void systems, both in terms of inner and outer experience. Volume articulations may be sharpened to take place within single parcels and leverage “sliding” properties of addition and subtraction. These options would refine the fractal dimension of urban space and the qualities it may boost in terms of openness, characterization of places and visual stimulation, keeping an eye on the multiplication of over-shadowing effects.

Our baseline model has considered the assignation of the same portion of volume throughout the whole set of property parcels. Variating the distribution of densities while keeping the control of the overall value may be a step forward in promoting the *specific quality* of design. We imagine, in this respect, the extension from a block to a series of blocks, where densities can vary according to an energy-conscious gradient, based on public space hierarchy and transport systems. In particular, informing patterns of concentration and distribution of volume loads through input “pointers” may be a base for evaluating the reach from notable locations: vertices standing for local and urban transportation hubs, service platforms, parks, and recreational facilities. Triggering a propagation of densities through arbitrary positions of vertices could also advise strategies for coordinating energy benefits of proximity, like critical mass, virtuous lifestyles, vitality and movement, with comfort of open spaces and solar accessibility, both normally intended as indirectly proportional to volume pressure. Speaking about movement, we imagine that the integration between parametrics and *network analysis* may result an extremely

[159] Cf. Brenna, S. (2015, October 7). Scali ferroviari. Un futuro tutto da ripensare. *Arcipelago Milano*. Available at http://www.arcipelagomilano.org/.

useful support to the rational localization of services, at both district and urban scale. The budding specialization of components assessing graph centralities, route choices and walkscores, seems to anticipate practices of tuning and optimization that could insist even on infrastructural efficiency.

Embedding codified regulations and incentives

Other investments may consider constraining diagrams so that they compute forms in strict accordance with overarching regulations or incentives. We can consider at least three examples of principles that may (re)generate form in this respect, all pledged to environmental concerns: one for built coverage, one for spacing, and one for passive and active solar systems.

With reference to built coverage, we can think of a recent Italian decree assuming minimum environmental criteria; in Italian, these correspond to *Criteri Ambientali Minimi* or *CAM*[160]. Proclaimed in January 2017, such decree compels new developments to provide at least 60% of permeable area; then, at least 40% of permeable area, or the 30% of the whole site, should assume the character of usable green surface. The generation of units may be programmed, in this case, not to exceed these tolerance limits.

With reference to spacing, the Italian *Civil Code*[161] defines the obligation to respect specific distances between constructions. In particular, article 873 states that bulks within finite parcels, when not adjacent or fused, have to comply with a mutual distance of three meters. Local regulations can even set greater distances. Even in this case, building bulks may be constrained not to violate minimum spacing.

With reference to solar systems, we can first imagine the embodiment of direct estimations, which would address and harmonize *active* strategies for PV potential of parametric forms. The selection of South and zenithal building faces may be associated with a custom solver, supposing, for instance, an indicative range of 10 to 20% efficiency. *Passive* strategies may benefit, in turn, from real-time calculation and visualization of faces and units reaching benchmark values of radiation. In both cases, the diagram could join energy demand with supply and viability, elements that, in the early design phases, can be decisive for re-orienting occupation toward substantial benefits in terms of on-site energy savings and productions. Also, we could conceive of implanting a well-proportioned reward system into the correlation of geometries, so that "fluctuation" of incentives translates to automated propagation of volumes, toward the most virtuous units.

Engineering integrated and multi-dimensional evaluation routines

Another development line may consist in expanding the matrix through further subsets of evaluation, balancing the sophistication of both variation and correlation patterns. These subsets could translate criteria of performance stemming from the contribution of existing and developing literature sources, which may originate from empirical findings and challenge common design patterns. Diversifying the pattern of evaluation would validate design rules across a multi-dimensional space of reflection, in line with the inherent complexity of our built environments (cf. Batty, 2007; cf. Puerari, 2011). Moreover, *divide et impera* strategies for designing diagrams (Woodbury, 2010), i.e. the organization of complex algorithms into a number of multi-polar specializations, would make possible to widen the scope of evaluative dimensions while preserving the parameterization of shapes and densities.

This approach would enable designers to breach theory of assumptions and practice of implications when factoring specific measures into the "equation" of urban development. This travels along the *customization* trend of parametric components, as well as the opportunity to combine selectors of geometry and math components into *user-defined* conditions of performance: both prospects we owe to *digital* parametrics.

[160] Retrieved from http://www.gazzettaufficiale.it/.

[161] Retrieved from http://www.bosettiegatti.eu/.

A further subset would allow for engineering an integrated assessment procedure that may compensate diversification of solvers with a convergence into synthetic judgements. In other words, it would constrain evaluation through a *weighting system*, which can be crosschecked and reformulated comparing outcome values and qualitative interpretations of local needs. A synthetic judgement would also inform or feed back into political values at stake. For example, we could consider introducing systems appraising the estimation of possible impacts through monetization, which typically characterizes *Cost-Benefit Analyses*. Parameterizing other models, such as *Multi-Criteria Analyses*, would be possible as well. Yet, preserving the focus on disaggregated measures would be an essential step for achieving different dimensions of spatial quality. Especially, these would facilitate a lot the awareness of alia interests. In this sense, parametrics may become an important *cognitive resource* for a decisional process (cf. Dente, 2011).
The development perspectives assumed for the model will need to be verified with respect to the main frictions we have discussed in the previous section. By now, we can consider them as hypotheses of further complexification, in line with a wider concept of spatial efficiency that, spurring from recognition of city systems as *complex systems* (Batty, 2007) may explore realistic options of bulk organization and design patterns.

3.4. Synthesis and conclusive recommendations: the need for conscious definition of parametric systems, due to the inherent complexity of urban occupation patterns

Our interest in parametric design crossed a demand for grasping those "blending" combinations of *shapes* and *densities* that constitute the burden of urban design, at least from a perspective of pure geometry. The absence of univocal relations between the two elements multiplies our responsibility for outcomes and assumes, in this context, the name of "*compositional problem*". In particular, this finalization met the hypothesis that parameterizing form could serve as a stratagem for prompting profiles of space occupation, both horizontal and vertical, to satisfactory performance, based on augmented gradients of solutions. Passing from a *discrete* to a *continuous* conception of massing is central to this concern, because the approach expands alternative selection of one-off designs toward the evaluation of transient, "decimal" mutations of form. This is grounded on *abstraction* through the assembly of a *diagram*, a "program" composing the genetic sequence supporting and informing these mutations. Programming form consists in governing conditions of emergence: "rules" that filter only fulfilling outcomes (Woodbury, 2010). This entails a major turn in conceiving final form, which is not anymore a static, *additive product*, but the responsive image of an *associative process* of generation. This distinction also mirrors the two paradigms of, respectively, *form-making* and *form-finding* (Tedeschi, 2014). The manipulation of a process, genotypic information at the base of geometries, can propagate change toward virtually infinite phenotypes, all showing autopoietic property (Schumacher, 2011).

In this framework, the parametric diagram performs as a solver of *constraints* expressing series of instructions; as such, it is the figurative manifestation of an algorithm. Parametric design finds in algorithmic modeling the practical room for variation, correlation and evaluation of geometries. The adoption of a composition perspective centered on urban form and energy implications led us to appreciate the expansion of digital parametrics toward generalized systems of constraints, which, unlike natural algorithms of analog experiences, enable custom definitions of rules for emergent geometries (Davis, 2013). Reflections upon urban morphology can benefit from this tendency, especially if we consider that ongoing specialization of components is openly oriented toward the simulation of compound forms (Galli, 2014). These include distinctive dimensions of urban realms, such as walkability, centrality and open space comfort. Energy solvers, though originally born for architectural purposes, can fully integrate a "control board" for informed design of urban patterns. In this sense, engineering the tectonics of variation, correlation and evaluation may support a responsive environment, where choices of spatial occupation, made through combined settings of parametric shapes and densities, would receive multidimensional feedback in real time. Developed as a plugin for Rhino, *Grasshopper* is currently the most popular platform for parametric-algorithmic modeling (Tedeschi, 2014). It is the center of that "ecosystem" of specialized solvers, which makes it a dynamic simulator. Factors of success include aspects not less important, like an active online support, a community of programmers and lay users, but also a wide "vocabulary" of associative instructions, and higher intuitiveness compared to previous systems, which is mainly due to the investment in advanced *visual scripting* language. All these features pushed us to consider *Grasshopper* as our support system of reference, a tool that could frame options of parametric occupation as guidance for predisposing the geometry of patterns to formal intelligence: guidance based on the parameterization of performance itself.

The focus has been the energy dimension of the compositional problem. This background proposed resorting to a continuous gradient of geometry for either *fine-tuning* or *optimizing* densification pressure over solar access, based on transient profiles of occupation. The hypothesis was that starting from abstract rules of occupation would allow for picking the most performing solutions out of that gradient, at least according to criteria chosen for variation, correlation and evaluation. Moving from parametric theory to practice, the three experiences selected for this purpose helped us acquire some knowledge about the importance of constraints definitions in determining reliable, significant outcomes. In truth, case studies were different in terms of setting (real or fictitious) and scope of application (straight modeling or guidance); yet, they all showed a common interest in how managing (horizontal, vertical) occupation parametrically could govern the multiple and "fluid" interactions between shape, density and energy effects. Our three layers of interpretation, namely *Technology*, *Expendability* and *Complexity*, made explicit reference to, respectively, support, sense and realism of criteria connected to variation, correlation and evaluation.

Crossing the three layers has been decisive for advising a supplementary approach to occupation: one that would draw value from conflicting obstructions, where *specific qualities* of form would sustain the differentiation of bulk patterns and intersect the simulation of few, but relevant distortion factors we may find in actual practice. This framework required the formulation of an alternative constraint system, based on allocating higher freedom to solid-void structures. Such freedom, consisting of distinct control levers for horizontal and vertical occupation, has been essential for reproducing the field of "complex equilibria" that characterizes real-world compositional problems. This relative freedom in organizing occupation has been a matter of intuitiveness as well. In effect, both shape and density settings (respectively, coordinates of bulks and plot ratio) have found effective translation into parameters close to the experience of a design environment. Besides, responsive feedback of evaluative "nerves", which traveled along dynamic 3D previews of indicators, led us to imagine an environment where designers may improve the *self-reflexive* understanding of their own choices (Schön, 1983). Despite being fairly meagre in absolute terms, results of both *optimization* and *fine-tuning* experiments show that "exploding" form into a continuous gradient may engineer the search of hidden, but performing combinations of shape and density settings. In our case, the search eventually led to the increase of both solar capture and volume intensity, despite the counter-intuitive nature of the two elements (optimization or *inverse design*); besides, a further probe of the gradient internalized the demands of occupation spurring from distortion factors, while still leaving room for harmony between energy and density (fine-tuning or *forward design*).

This has been, clearly, a rudimentary application, whose partiality originates from the non-exhaustive picture of selected practices. Yet, we can consider it as an inspirational starting point for future refinements that, by the way, would intercept a trend-line that ongoing specialization of components seems to have already plotted. It is a hypothetical model where occupation of space, while embracing complexity and *specific quality*, achieves properties that approach a more realistic perspective of urban design guidance. Within this framework, simulation would not perform as passive or *ex-post* feedback, but, rather, as an active and inborn "force" conditioning the efficiency of forms. This is something that, in the future, may fulfil the "missing link" between analysis, design and evaluation that has been characterizing planning discipline. At the same time, we hope not to give the impression that parametric tuning and optimization shall substitute the alternative selection of creative solutions. Rather, we conceive them as support systems for thinking, informing and filtering design concepts at stake.

In theory, the explosion of "elastic" gradients, based on the sliding control of parameters, is the natural consequence of integrated procedural networks, whose outcomes claim adaptive, or autopoietic properties. In practice, translation into working and reliable constraint systems, which are what actually supports such gradients, is not as direct as it may seem. In particular, the "transitional" power of parameterization comes at the cost of inertias and frictions that are intrinsic to the abstraction of form. Most of the literature tends to cover up how (hardly) models come to be. Considering that raising complexity means dramatizing these frictions, hardship of practice concerns us directly. Both examination of case studies and formulation of a complementary model have been incentives to consider the general obstacles encountered in practical parametrics, which found confirmation in dedicated literature. Specifically, the former inspired a reflection upon the systematic subjectivity of definitions; the latter compelled to acquire critical understanding of abstraction through directed diagrams. Conditioning geometry to performance is inherently subjective, though we may strive for considering the intelligence of form as "innate" or "embedded". This happens with all dimensions of a constraint system: variation, as well as correlation and evaluation. These require well-pondered choices of input (variation), standard and special components (correlation and evaluation). This also implies that the "*optimum*" of parametric optimization is not only heuristic, but inevitably spurious. There is no real optimum unless for specific conditions of occupation.

Other problems rise from the translation of intuitive knowledge into the unambiguous and codified syntax of algorithms, which is specific to prospects of complexification and strictly connected to our interface with the parametric diagram. Being *digital* computation our reference system, what is accessible for us mentally may be practically difficult for the electronic brain. This remark implies that we cannot speak of an "egalitarian" interaction between man and machine, between designer and parametric diagram, because human elements shall adapt their language and way of thinking to what computers can understand, that is, to precise grammar and vocabulary of components. In other words, digital computation, which we assume as essential for sophisticating conditions of occupation and performance, implies an unfavorable compromise for human elements. *Visual scripting* can become ever more intuitive and communicative, but the integral responsibility of design consistency and the compliance of definitions with intuitive knowledge is always on behalf of the designer. Virtual algorithms, unlike natural algorithms of material computation, force abstraction toward generalized parametric systems, but this, while supporting increasingly complex dynamics of association, also results in the multiplication of subjectivity and responsibility.

> *«The main shift is one from a high fidelity in the manifestation of design concepts to a high fidelity in the expression of the logic of design concepts. To use a metaphor, it is a shift from focusing on the face of a watch, to a focus on the internal mechanics of the watch. I disagree that it is "just a tool", but I do agree that it should also not be the "purpose" of a design. Parametric design is a shift in thinking of how we get from design intent (what we want to do) to design response (how we go about doing it)»*[162].

Within a context of increasing complexities, submitting intuition to rules that are strongly deterministic dramatizes the trouble with modeling, proportionately (Davis, 2013; Smith, 2007). The directed nature of diagrams makes them highly refractory to change and adaptation: they require users to untangle imagination into strictly procedural syntax, where there is no room for recursive thought. The sharper the intricacy of associations, the more probable the collapse with change. Propagation, while central to the autopoietic intelligence of form, has another side, which makes algorithmic systems overly sensitive to unexpected errors, where the "error" can be not only a "wrong" component, but the absence or even the excess of instructions compared to the appropriate definition. The overload of parameters can also be a problem, because detailing urban form with specific quality demands a generous number of dimensions for the model.

These problems of practice closely relate to the transposition of a tool conceived for definite purposes to newer domains (Fraser, 2012; Zarei, 2012). In-built components for processing geometries, as well as special utilities released for urban simulation, can support the reproduction of bulk systems, but we cannot negate the origins of a parametric tool like *Grasshopper* as a modeler for product design, engineering and basic architectural purposes. As recalled by Malcolm McCullough (2006), these are domains

«whose subject matter is engineered form itself» (McCullough, 2006, p. 14).

Loosely speaking, domains where the management of forms manifests generic quality as a standard. The urban context performs, instead, as a complex system (cf. Batty, 2007) that implies much more wide-ranging *degrees of freedom* than the ones of product engineering and design purposes.
Hence, pondered use should be encouraged: designers willing to engage with forms as complex as urban ones need to be aware that, according to the "laws" of parametrics, they should adapt to likewise hard endeavor and understanding. Constraint systems can inform geometry stretching to virtually endless configurations, but at one condition: they do what we, as designers, *ask* them to do, not (necessarily) what we *expect* them to do. The responsibility of design processes, i.e. the exact consistency of outcomes to intended rules, is always on behalf of the human element.

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[162] Jabi, W. (2014, April 2). Re: Parametric VS Computational Design [Blog comment]. Retrieved from http://www.immaginoteca.com/parametric-vs-computational-design/#comment-22983.

Through our theoretical and practical experience of parametrics, we hope to have acquired, at least, a critical consciousness about potentials and limits of this technique. The cross-fertilization of these two sides led us to acknowledge that parametric design is something far from simplistic conceptions like "automated" or "ready-made projects". In particular, as we imagine hypothetical developments of our exercise, the work may ground further reflections upon the management of even sharper complexity, programming the emergence of efficient forms based on a wider variety of perspectives. The honest appraisal of payoffs between benefits of exploding form into gradients on the one hand, and substantial costs (cognitive, temporal) on the other, found its place along this same line of reasoning, stepping beyond the blur of theoretical narratives.

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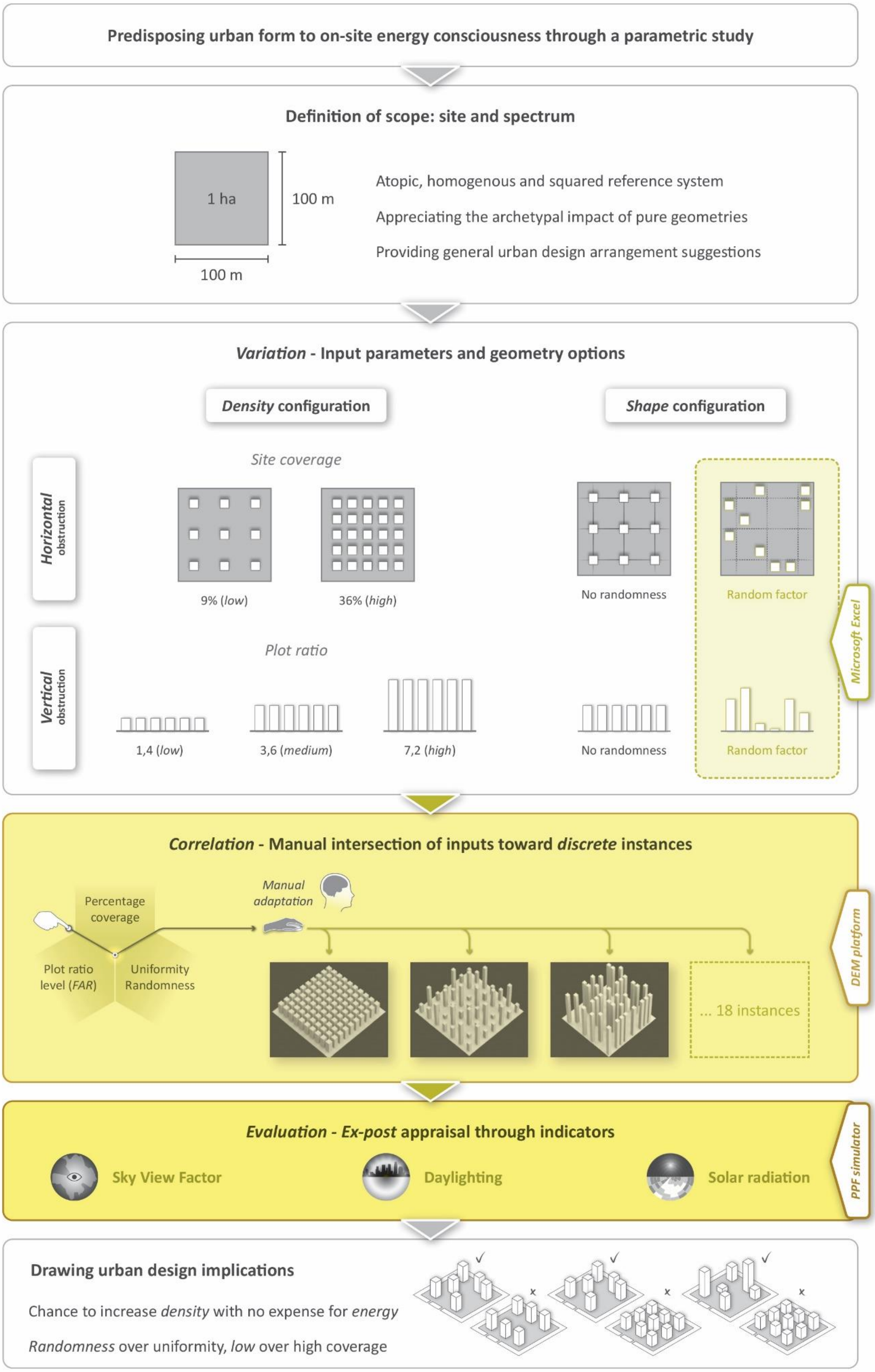
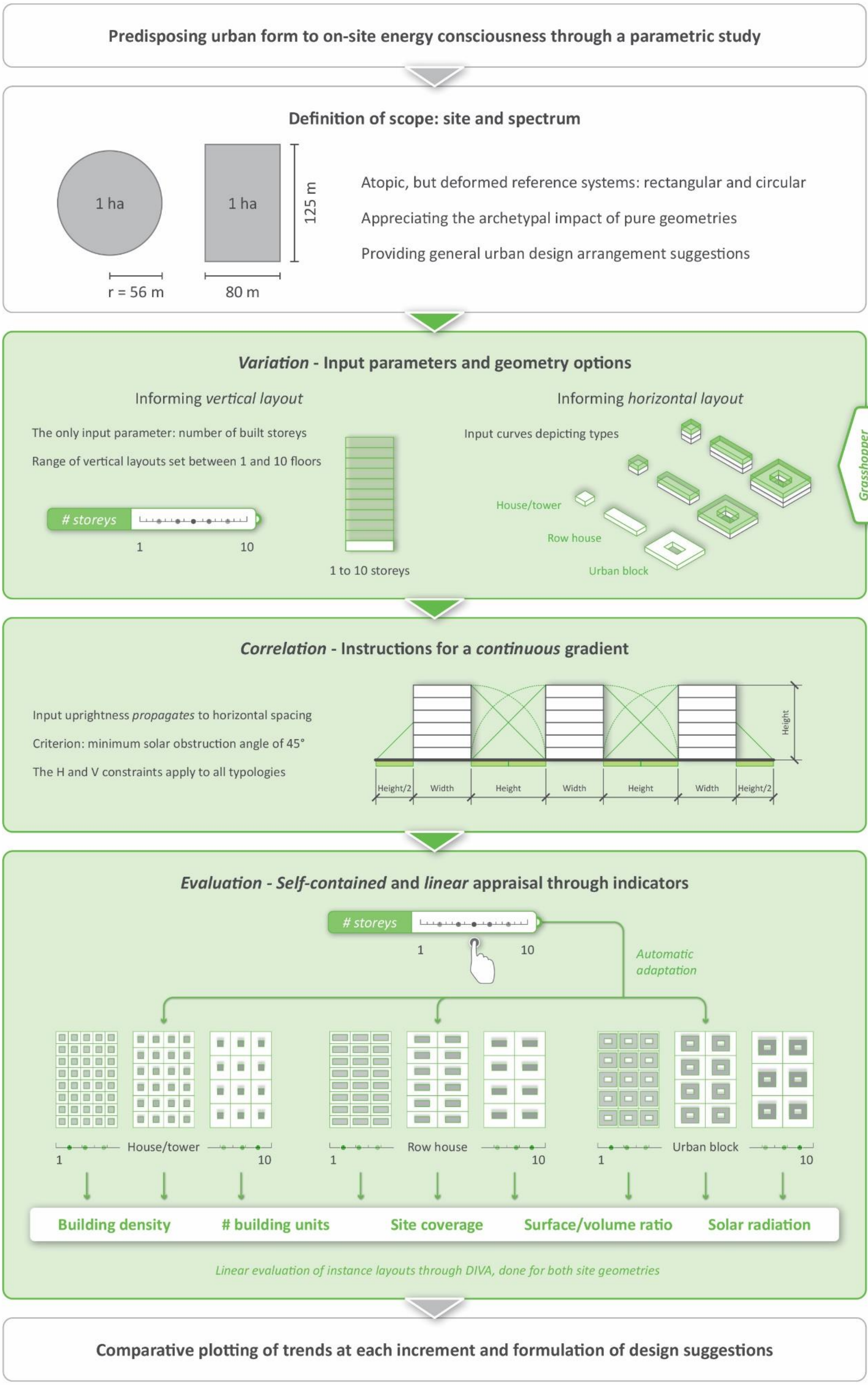
ATTACHMENTS

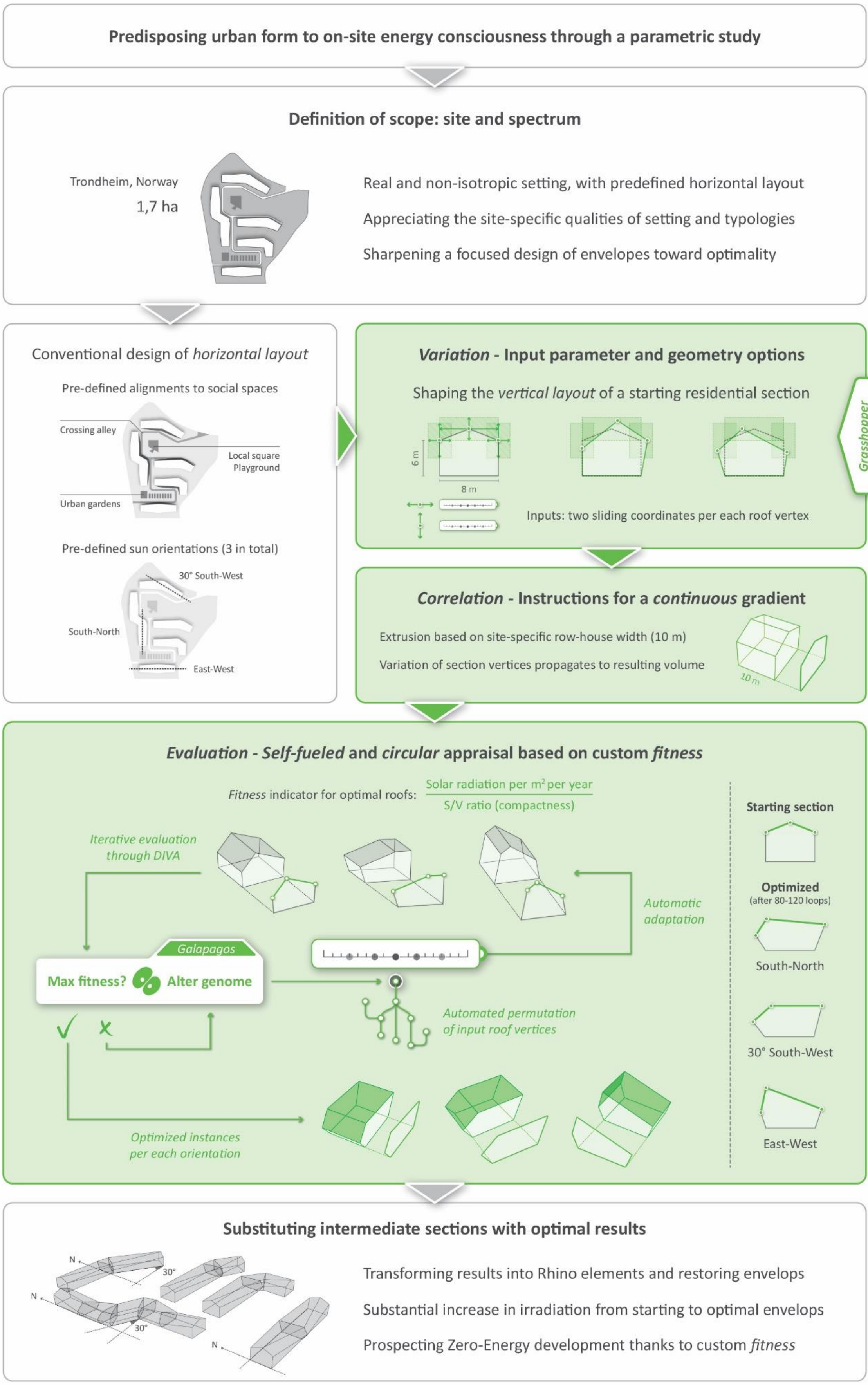


219

Att. 1. Synthesis of case study *A*. Yellow shades depict the different non-parametric environments used for variating, correlating and evaluating form.



Att. 2. Synthesis of case study *B*. Unlike what we have seen in the previous case, the whole stream of variation, correlation and evaluation procedures takes place within the same parametric platform (*Grasshopper*).



Att. 3. Synthesis of case study *C*. Similar to case B, the parametric environment of *Grasshopper* proves to sustain the whole process of generation, this time involving feedbacks on performance as an active molding force.