3D urban data to assess local urban regulation influence

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Abstract

Systematically assessing the influence of new urban plans is an important challenge for designing them efficiently. In this paper, we propose a method to assess the influence of local 'Right to Build' regulations on constructibility. Our method is based on an optimization algorithm that generates building configurations. This method requires a geographic model that supports the formalization of the Right to Build regulation in order to check if a building respects it. The proposed approach relies on the trans-dimensional simulated annealing optimization method, which produces building configurations composed of a set of parametric objects (boxes in our implementation). Our proposition is released as the SimPLU3D Open-Source project (http://ignf.github.io/simplu3D/). In this paper, we present some tests and results based on this implementation and a use related to the assistance to 'Right to Build' designers.

Keywords: 3D data, 3D analysis, urban regulation, simulation, building generation, optimization, simulated annealing

1. Introduction

Cities are concerned with many economical, social or environmental issues. In order to regulate their evolutions, Master Plans are designed by municipalities or administrations with the support of public discussions. These plans

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may be defined at different scales according to their aims and the concerned phenomenon (traffic, air pollution, constructibility, etc.). They are applied to specific territories and their content combines spatial data (organized in maps) and legal information (compiled in texts). One issue concerning these plans is to assess their effectiveness and notably to evaluate their forseen influence.

This paper focuses more specifically on local urban constructibility regulations. This type of regulation, very frequent in industrialized countries, aims to define rules that regulate how buildings can be built on a parcel. Respecting these rules is mandatory to receive a building permit from the local administration. These rules can cover the 3D morphology of buildings, their aspect and their functions. They are generally expressed through free-formed texts. Thus, two issues about the exploitation of this type of regulation can be highlighted. (1) **Non expert citizens** may have difficulties to understand these rules expressed in legal terms. Most citizens do not have the necessary skills to assess how a district may change by implementing a new plan or what it can be possible to build if they buy a parcel. (2) **For local administrations**, even if they have the necessary skills to assess the influence of a plan on one parcel in terms of constructibility, it is extremely time consuming to assess the influence of the plan on an entire city or to evaluate different plan scenarios.

In this context, we propose an approach to make the information conveyed by these plans more tangible, by simulating 3D buildings consistent with constructibility regulations.

Providing a 3D modeling helps evaluating the potential impact of urban regulations for different topics such as floor area ratio assessment or solar energy development [1]. It also improves public participation by using 3D geovisualisation application to illustrate the plans [2].

Our work is focused on the French regulation expressed through LUPS (Local Urban Planning Schemas). These plans are local and their contents are not harmonized on the whole French territory. Thus, in our approach, we consider a generic formalization of local urban regulations that offers the possibility to manage local particularities. Nevertheless, our proposition can be extended to

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be adapted to regulations of other countries.

2. Related work

Different works intend to ease the comprehension of urban regulation in 3D through several types of approaches:

- linking regulation to related geographic features in a 3D viewer [3];
- producing buildable hulls from geometric constraints [4, 5, 6];
- offering the possibility to explore a predefined set of parametric buildings respecting rules [7];
- generating buildings [8, 9, 10] or
- proposing extensions to existing buildings [11].

Among these works, building generation offers, in our opinion, the most promising results as it directly provides objects that may be built.

However, a first limit of these approaches is to be based on a small set of rules that does not represent the diversity of existing urban regulations. In this paper, we propose a generation process based on a generic extensible model of rules. Another limitation is that most existing generation processes proposed are based on heuristics, for example grammar based generation, which requires prior knowledge about the generative steps of the building configurations. Thus, using such approaches requires to define the right generation process that fits with every configuration and to adapt it with the different possible regulations.

Building generation methods are explored in various fields such as architecture [12], urban planning [13], geosimulation [14], building reconstruction [15] or computer graphics [16]. The goal of the generation differs according to the domain. [17] distinguishes geometric from behavior based approaches, even if they are not always discordant. Behavior based approaches aim to produce buildings by integrating human processes and decisions whereas geometric approaches are designed to create fast and visually believable objects. As the objective of this

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paper is to simulate urban regulations, it is necessary to integrate preferences of different agents that design buildings in order to assess the impact of the rules for different actors (for example, households or promoters). Generally, these preferences are translated into utility functions that agents try to maximize.

To maximize such functions, optimization methods are used such as Multi-Agent Systems [14] or meta-heuristics like evolutionary algorithms [12] or simulated annealing [18] combined to geometric generative methods like primitive instancing [19, 1] or shape grammars [20]. In order to integrate constraints, a large set of methods and their comparison are described in [21] including rejection, penalization of the optimization function or fixing solutions that do not respect constraints automatically.

3. Global proposition

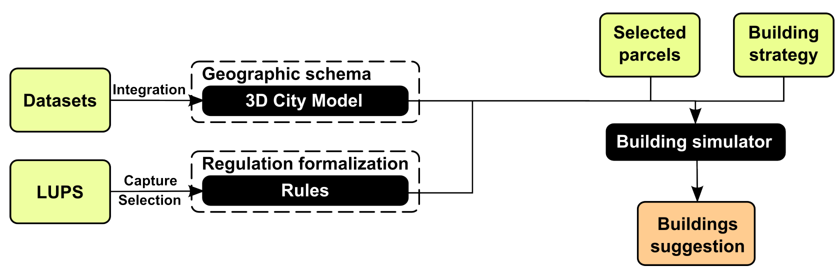

Figure 1: Global proposition of the paper.

The global proposition of this paper is synthesized in figure 1. In order to exploit knowledge about local urban regulations, we propose a model that allows both a generic formalization of rules and a generic formalization of geographic features mentioned in these rules. These aspects are briefly introduced in section 4. In order to simulate buildings, we propose an approach based on a trans-dimensional simulated annealing algorithm (TDSA) [22], which uses our proposed model, and which generates building configurations according to a strategy on a set of parcels (section 5). An implementation and some experiments are then presented (section 6).

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4. Urban regulation model

In this section, we briefly introduce the content of French LUPS (section 4.1) and the scope of the model (section 4.2. Then, we provide a short description of the 3D geographic schema (section 4.3) and a presentation of elementary geometric constraints (section 4.4). Finally, the proposed rule formalization is introduced (section 4.4.1) and the ability of the model to be applied on real documents is discussed (section 4.4.2). In this paper, we only give a brief presentation of the urban regulation model based on an already published complete model [23].

4.1. Short Introduction to LUPS

3D building morphology of French cities is regulated at a local scale through the Local Urban Planning Scheme (LUPS)[1]. Each LUPS specifies a zoning plan where each zone is assigned a type[2]. For each type or subtype of a zone, 14 or 16[3] articles have to be defined (table 1). These articles have normalized titles imposed by the French National Urban Code ([4]). For instance, it induces that, for all French LUPS, article number 10 always limits the height of buildings. Nevertheless, the contents of each article are free; each municipality can express its own set of regulations. A great diversity appears in the expression of rules from the same article in different LUPS. Thus, it is impossible to list all possible rules.

4.2. Scope of the model

In LUPS, the different rules mention geographic features and associated information. For instance, let us consider the following rule (geographic features are in bold, relationships and attributes are underlined):

[1] LUPS for PLU: Plan Local d'Urbanisme.

[2] The typology of such zones includes urban zones type U), zones to be built (type UA), agricultural zones (type A) and natural or forested zones (type N)

[3] According to LUPS version.

[4] Code de l'Urbanisme

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#	Title of the article	Scope
1	Forbidden or allowed land uses	Project
2	Land uses subjected to particular restrictions	Project
3	Access and roads	Parcel
4	Technical networks	Parcel
5	Terrain characteristics	Parcel
6	Building location related to roads and public easement	Building
7	Building location related to parcel borders	Building
8	Building location related to other buildings	Building
9	Building footprint	Building
10	Building maximal height	Building
11	Exterior appearance	Obligation
12	Parking	Obligation
13	Free space, vegetation and protected woods	Obligation
14	Floor area ratio	Density
15	Energetic and environmental performances	Technical requirement
16	Communication network and infrastructures	Technical requirement

Table 1: Articles of a LUPS and scope of the articles: articles represented with grey lines are not considered in our proposition.

If the width of a **road** is smaller than 7 m then distance between the **borders of this road** and adjacent **buildings** must be higher than 3 m

in order to properly implement this rule in a GIS, roads, borders of roads and buildings have to be modeled, as well as adjacency and distance relationships between roads and buildings, but also information about road width and building height.

We synthesized the required information by looking up LUPS from several municipalities and a best practices summary [24]. By analyzing these texts, we extracted the relevant geographic features, relationships and information used to define rules. We synthesized the most common forms of rules in accordance with the scope of our work. Rules that do not concern buildings or parcels are ignored. This filter suppresses from our scope articles that consider parking or vegetation for example. Furthermore, we do not integrate rules referring to architectural elements of buildings too detailed to be available on whole city

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databases, for example balconies or façade decorations.

4.3. 3D geographic schema

As concepts of urban regulation are three-dimensional, the proposed model includes 3D objects, relations and attributes. It synthesizes all information mentioned in LUPS regulation according to the fact that they respect previous mentioned filters. The proposed model is based on existing geographic standards; the interest is to be interoperable and to highlight necessary information in these standards for ours needs. Thus, different standards are integrated:

- CityGML for 3D topographic features (buildings, roads and terrain) [25];
- Inspire specifications for cadastral parcels [26];
- CNIG/COVADIS French specification [27] for the description of graphically specified constraints.

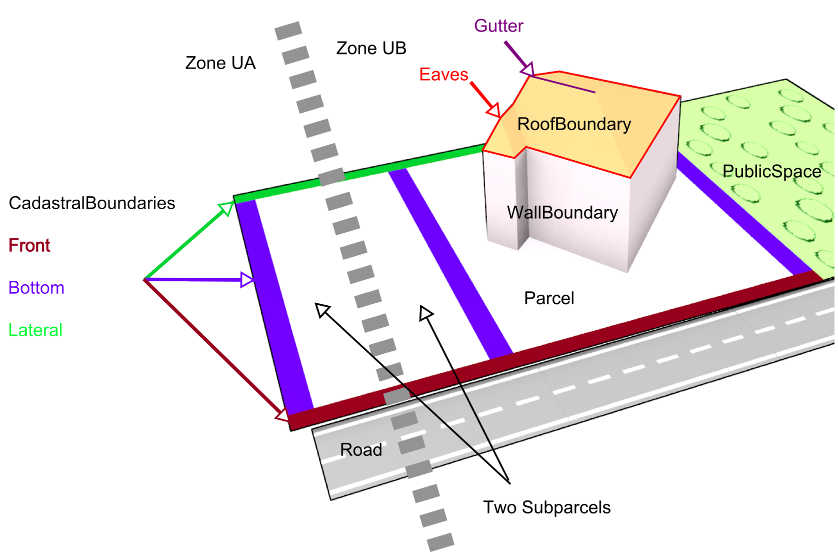

Figure 2: Sample of object classes representation in the model with some key concepts.

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Key concepts of this model are schematized in figure 2. Zones define the area on which different regulations are applied. A parcel can be located at the intersection of several zones, it is then decomposed into several sub-parcels on which a unique regulation is applied. For each parcel, each boundary has a type according to its localization in the parcel (front, bottom or lateral) and is linked to neighbor objects (road, public space or another parcel). If this categorization is used for the whole French territory, type determination varies according to local definitions. Buildings lay on a parcel and are composed of roof boundaries and wall boundaries. Some extra-information, relevant for rule interpretation, is added to roof boundary such as eaves and gutters.

Figure 3 represents an overview of our schema[5] and shows the origin of the different classes. On this view, extensions are proposed to connect the different used standards together. For example, the *SubParcel* class is introduced to integrate the fact that a parcel can be located at the intersection of several zoning plans: different rules are applied according to the part of the parcel. Thus, in order to model rules, it is necessary to consider that parts of a building on different *sub-parcels* have to respect different sets of rules. The concept of *sub-building* is used to model this. A *sub-building* is attached to one sub parcel and a building to a BasicUnitProperty. For existing buildings, the model is based on CityGML LOD2 buildings. LOD1 buildings are also integrable, but the lack of roof implies that some constraints cannot be estimated. LOD3 buildings may be used in the future, the presence of windows, notably, allows the integration of visibility rules (for privacy preservation, for example).

4.4. 3D geometric operators

In order to check the rules, several geometric constraints can be used to form OCL expressions. These geometric constraints are checked on the generated configurations. Currently, the available constraints can be divided into five categories:

[5] The whole schema is available in [23].

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- **Distance** to the different objects of the environment (roads, other buildings, parcel limits, according to its type);
- **Building height** with several options according to considered low altitude reference (for example, lowest point of the terrain or of the building) and high altitude reference (height is measured to the top of the building or to the gutter) ;
- **Prospect** constraints define a plane generated from a reference object of the environment[6]. The building must be built under it ;
- **Built ratios** may constrain the built surface or the total floor area;
- **Alignment**: Building footprints may have to be aligned to the road or to recoil lines or be stuck to gables of existing buildings in order to preserve building continuity.

[6]The plane is defined by a height against a reference object and a slope

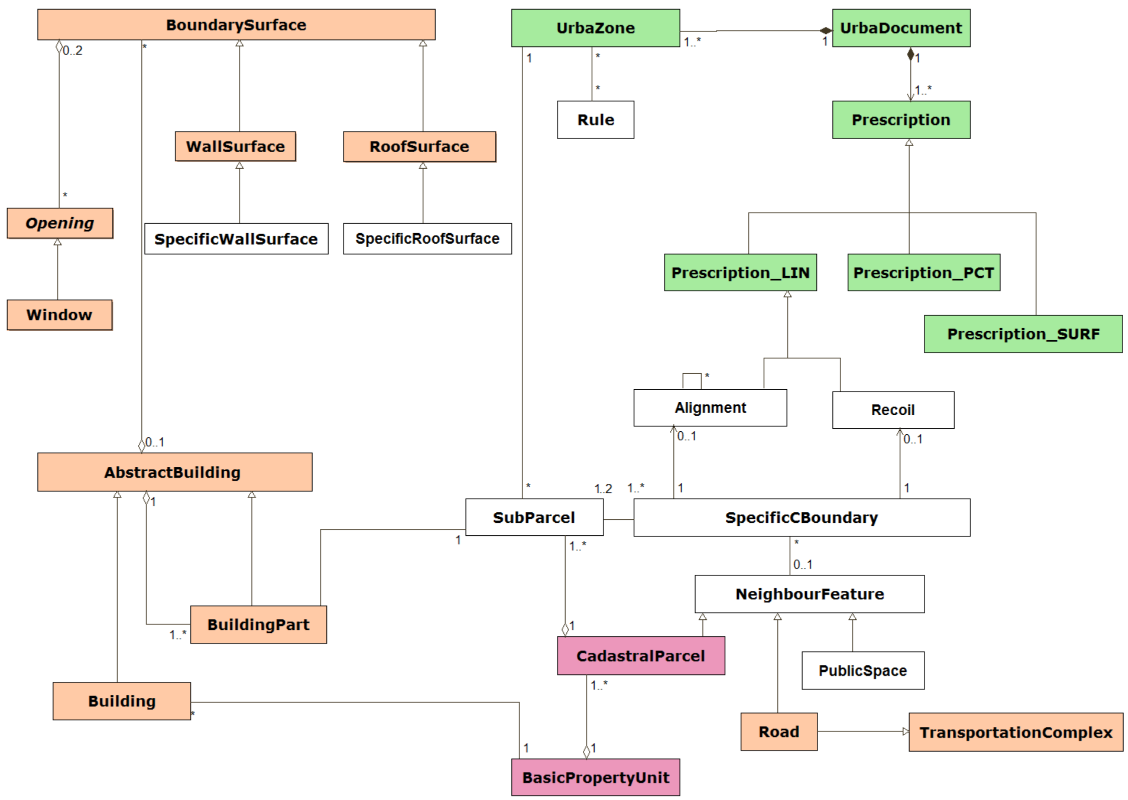

Figure 3: Overview of the global model for geographic features, information and relationships. Purple classes are described in [26], orange ones in [25] and green ones in [27]. White classes are addition for specific needs. Only classes and relationships are represented.

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4.4.1. Rules formalization

Considering that all relevant rule elements are described in our model [23], we propose to formalize rules with OCL (Object Constraint Language), designed by [28] and standardized in [29]. This language allows the description of constraints with the support of a UML model. It offers the possibility to form rules by the combination of specific OCL vocabulary and classes with attributes and relationships from the UML model. The major benefit of OCL formalization is to offer the possibility to express constraints by using the elements of the model directly. With the addition of specific vocabularies, it allows the possibility to perform operations on object lists such as aggregation or counting. This language is, for example, used in Geographic Information Systems to check integrity constraints [30, 31].

In our proposition, each rule of LUPS is translated into an OCL expression like in the following example:

Textual form of a rule in a LUPS

The distance between a building and the borders of its parcel must be greater than 3 m.

Translation in OCL

```
context CadastralUnit inv:
self.getBoundary().geom -> forAll(g |
self.getBuildings().footprint.distance(g) ≥ 3.0)
```

4.4.2. Feedback about rule conversion into OCL

As the regulation is defined by the local administration by deriving the general articles from the French National Urban Code (cf. table 1), some specific local concepts may be absent in our model. Nevertheless, our approach aims at being easily extensible. In order to define new rules, one can extend the data model or define new OCL rules on the data model. This formalization may also

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be interesting to exchange rules between municipalities if a common schema can be established in order to share effective local practices. The full description of our model and rules formalization is presented in [10, 23].

For our experiment, we consider that the current model directly covers around 90% of the LUPS regulation according to previously mentioned filters (section 4.2). In chapter 7 of [10], the author writes a commented translation of the Strasbourg regulation into OCL. Globally, non-considered rules are those that are out of scope because they focus on particular architectural objects (lifts, balconies, etc.) or require human judgment (harmony regarding the existing urban fabric) that cannot be integrated into such a system.

5. Method for building configurations generation

Considering a given parcel, we propose, in this section, a process that generates building configurations respecting urban regulations. The main hypothesis of our method is that a builder agent aims at optimizing some criteria (for example, to maximize the area of building floors or to minimize the area of building footprint). Thus, the issue comes down to an optimization problem under constraints.

In our method, we choose to base our optimization process on the Trans-Dimensional Simulated Annealing method (TDSA) [32]. During the design phase, we consider different methods to solve this problem such as Multi-Agent System or Evolutionary Algorithm. We choose to solve it by using the TDSA method because we find that this solution is more adapted than:

- **Multi-Agent System**: according to [33], Multi-Agent System offers better solutions when there is a need to make agents communicate, when the problem can be decomposed into subtasks and when the process requires agents adaptations or modifications during the process. It is not the case of our problem as the simulation only considered objects inside a parcel. Furthermore, the authors notice that it may be nearly impossible to assess the quality of the optimized solution. This is an other drawback as we

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are aiming to provide a method that adapts to different configurations (in termes of parcels or regulations) ;

- **Evolutionary Algorithm**: the differences between evolutionary algorithm and simulated annealing methods are discussed in [34]. The author explains that even if the vocabulary are different the major difference is the presence of crossing operators for evolutionary algorithms that produce a new solution by mixing two other ones. The author highlights that this operator has to be chosen cautiously in order to provide a real advantage during optimization process. In our problem, it is very difficult to find a relevant crossing operators as the building configurations may be located at different positions inside the parcel and as they may have very different shapes, there is no obvious solution to relevantly mix them. Furthermore, one important advantage of the TDSA, is that it determines by itself the optimized number of objects to create inside a parcel. It is useful to simulate different behaviors of constructor agent or to be robust according with parcel size. There are some possibilities to do this with evolutionary algorithms or genetic programming [35].

5.1. General description of the generation algorithm.

To process the algorithm, several input to produce optimized building configurations are necessary:

- LUPS rules ($rules$) and potentially other constraints based on geographical model or spatial indicators to avoid unexpected configurations. The rules are expressed in OCL as described in previous section ;
- optimization function (μ), composed of elements from the model or 3D spatial indicators ;
- a geographic environment (E) modeled according to our proposition presented in the previous section ;
- a parcel, on which the building configuration will be generated.

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At each step of the TDSA process [36], a configuration C_{mod} is generated from a modification of a state C_{conf}. Each configuration is composed of a set of n objects, n may vary according to successive modifications (the object class is described in section 5.2). The applied modification is chosen among a set of proposition kernels Q_i that provides the different possible moves that may be applied (kernels are presented in section 5.3). The new configuration C_{mod} is evaluated through the OCL rule checker (section 5.4). If the rules are respected, a probabilistic function, that depends on the optimization function μ, determines the probability α to keep the state C_{mod}. If $\mu(C_{ini}) \leq \mu(C_{mod})$, then $\alpha = 1$, in the other case, $\alpha > 0$ in order to avoid the process to be stuck in a local optimum. The acceptance of the configuration is presented in section 5.5. α is parametrized by a temperature $\mathcal{T}$ that decreases during the process and reduces the value of α when a modification lead to a worse configuration. Parameterizations of the TDSA (initialization, stop condition and temperature function) are discussed in section 5.6.

The proposed algorithm (algorithm 1) is iterative and described in the next sections. The simulated annealing is called trans-dimensional when kernel modifications allow a change of dimension for the configurations (*i.e.* the number of object in a configuration). Thus, the dimension of the optimal configuration[7] is automatically determined by the method.

[7]Number of objects that compose the configuration.

Data: $rules$, μ, E

Result: C_{conf}: final configuration

Initialization of the configuration $C_{conf} \leftarrow \emptyset$;

repeat

    `/* Random choice of a modification among several proposition kernels (described in section 5.3) */`

    Sample $i \sim q(C_{conf})$;

    `/* Generation of` C_{mod} `from the modification; */`

    Sample $C_{mod} \sim Q_i(C_{conf})$;

    `/* Check of the respect of rules formulated in OCL (section 5.4) */`

    if *isChecked*(C_{mod}, $rules$, E) **then**

        `/* Determination of a probability` α `(section 5.5) of acceptance of` C_{mod} `*/`

        $\alpha = min(1, e^{-\frac{\mu C_{mod} - \mu C_{conf}}{T}})$;

        $r \sim [0;1]$;

        if $r \leq \alpha$ **then**

            $C_{conf} \leftarrow C_{mod}$

        end

    end

until *convergence*;

return C_{conf}

Algorithm 1: Simulated annealing for the generatation of building configurations

5.2. Building configuration model

As our proposition is based on a TDSA instantiation, it tries to optimize an optimization function by generating a configuration of n objects. Each object is defined by a set of parameters. In our approach, a configuration is composed of a set of boxes $b \in \mathcal{B} \subset \mathbb{R}^6$. A box $b = (x, y, l, w, h, \theta)$ is discribed by six parameters: position of its center (x,y), length (l), width (w), height (h) and

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orientation (θ). Parameters are illustrated in figure 4.

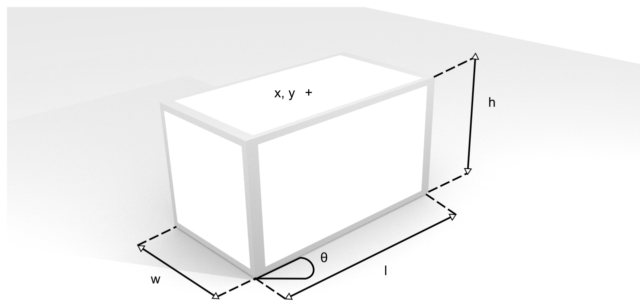

Figure 4: Parameters of a box.

The notion of building configuration can be defined differently according to the considered use case. For example:

- with $n = 1$, one building is equivalent to one parametric object. It can be used to simulate similar individual buildings ;
- for $n \geq 2$
  - with connected objects, it is possible to generate a unique complex construction (such as administrative or industrial buildings) composed of these objects ;
  - with no connection constraints, it represents a set of complex buildings, for example to simulate housing estate.

5.3. Proposition kernels

Search space exploration is supported by a set of proposition kernels. A proposition kernel $Q_i, i \in [\![1; n_q]\!]$ is randomly chosen and applied on a random box of a current configuration. In our experiments 6 kernels are used:

- Q_1: addition/deletion of a box;
- Q_2: translation;

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- Q_3: length change;
- Q_4: width change;
- Q_5: height change;
- Q_6: rotation.

Q_1 kernel changes the dimension of the current configuration. If box addition is chosen, a new box is added with parameters sampled according to the definition of the search space:

- $xmin \leq x \leq xmax$[8];
- $ymin \leq y \leq ymax$[9];
- $0 \leq dmin \leq l \leq dmax$[10];
- $0 \leq dmin \leq w \leq dmax$;
- $0 \leq hmin \leq h \leq hmax$;
- $0 \leq \theta < \pi$.

Several parameters of the search space can be determined according to the parcel shape. The sampling of center coordinates is processed according to the method described in [37]. If box deletion is chosen, a random box is removed from the current configuration.

For Q_2 to Q_6, a modification is applied to a box of the current configuration. Thus, for a box b = (x, y, l, w, h, θ), modifications produce a box b' with following parameters according to chosen kernel:

- Q_2: b' = (x + R $\eta_1 \cos(\pi\eta_2)$, y + R $\eta_1 \sin(\pi\eta_2), l, w, h, \theta$);
- Q_3: b' = $(x, y, l + \eta_1 dl, w, h, \theta)$;

[8] xmin and xmax are determined according to concerned parcel bounding box.
[9] Idem for ymin and ymax
[10] dmax is smaller than the length of the bounding box of the parcel.

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- Q_4: b' $= (x, y, l, w + \eta_1 dl, h, \theta)$;
- Q_5: b' $= (x, y, l, w, h + \eta_1 dh, \theta)$;
- Q_6: b' $= (x, y, l, w, h, \theta + \eta_1 d\theta)$;

with:

- $(\eta_1, \eta_2) \in [-1, 1]^2$ random variables;
- $(R, dl, dh, d\theta) \in \mathbb{R}^{+*}$ are coefficients that fix maximum displacement amplitudes. These parameters must be low enough to avoid too frequent modifications that result to configurations not included in the parcel. Nevertheless, these coefficients must be high enough to allow the exploration of a relevant part of the search space in order to speed up the convergence. For instance, we empirically use these values in the following experiments: $R = 2m$; $dl = 2m$; $dh = 2m$ and $d\theta = 10°$.

  Globally, a bad fixing of these parameters will lead, in extreme cases, in a decrease of the probability to reach an optimized configuration and will require more iterations to reach interesting results.

5.4. Rules management during optimization process

5.4.1. Rules checking

The aim of this step is to determine if the configuration is consistent with the LUPS rules. In fact, it consists in evaluating every OCL expression for each object of the environment. In the checking only concerns buildings, it is sufficient to process in the neighborhood of the aim-parcel in order to decrease computation time. This concerns objects related to parcels touching the project and parcels located on the other side of adjacent roads. This scope is adaptable according to rules influence area.

For rule management, we choose a rejection approach for more genericness (*i.e.* to be compatible with OCL expression) and to ease extensions, as it is easier to check if an object respect rules than assessing how much it breaks it. If a modified configuration does not respect rules, it will not be considered for

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the following steps. New modifications will be then randomly chosen until a configuration respecting rules is produced.

In order to perform efficiently a huge quantity of OCL rules checking during the process, we proceed to some adaptations from the solution presented in [23]. To begin with, some rules implies geometric "strict" constraints (For example: distance between building and road borders must be equal to 5 m). As the search space is continuous, it is very improbable that the system proposes a building respecting such constraints. Thus, it is necessary to create some margins to ease sampling (For example, it will transform previous rule into: distance between building and road borders must be contained between to 4,5 m and 5,5 m). Some post-processing steps may be necessary in order to correct such approximations.

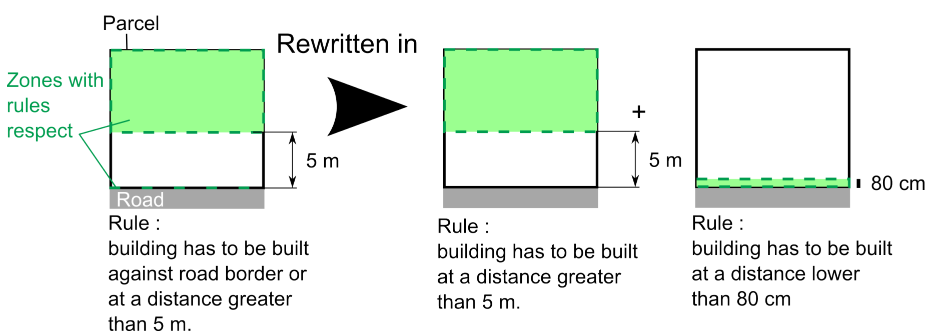

Figure 5: Rewriting of a rule from two rules that create non-connected search space and strict constraint.

Another difficulty is due to the presence of disjunctions that can cause some non convex sub-space in the global search space. For better optimization results, it is recommended to rewrite the rules to isolate the different sub-spaces, to run the optimization process on these sub-spaces. Figure 5 illustrates above issues and shows how to rewrite these rules. In our implementation, the optimization process is executed for both rules and the best configuration is kept.

5.4.2. Reduction of search space

In the basic process, the regulation is composed of only OCL rules with no prior knowledge about these rules in order to be as generic as possible. Thus,

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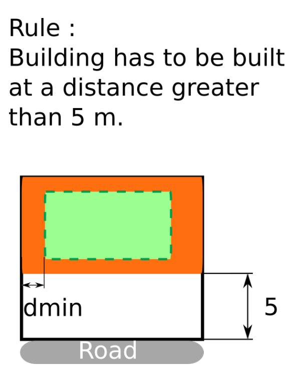
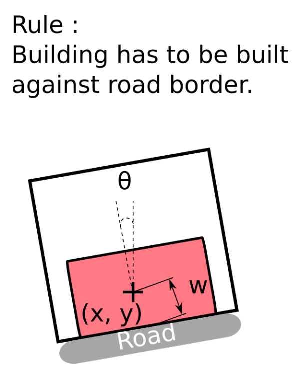
regulation is a black box that returns *true* if the regulation is respected and *false* otherwise.

Nevertheless, it is possible to add knowledge for each OCL sentence in order to reduce the search space and to improve the performances of the algorithm. A first strategy may be applied on distance constraints. By interpreting the different distance constraints, it is possible, in 2D, to build a polygon that respects the distance to the other objects (figure 6a). The combination of these polygons produces a surface that reduces both the sampling surface (of box center) and the maximal dimensions of the boxes.



(a) Strategy for distance constraint: the centroid is necessarily sampled in the green rectangle to respect rules



(b) The orientation and the width of the pink box is determined by its centroid

Figure 6: Two strategies to reduce exploration space according to distance and alignment constraints.

A second strategy may be applied on alignment constraints. When boxes have to be aligned to a line segment, the constraint forces, for a sampled centroid (x,y), both the orientation (θ) and width (w) to be set as unique values (figure 6b). These parameters are no longer necessary to describe the box. Thus, the dimension of the box can be reduced from 6 to 4.

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5.5. Optimization function and acceptance of the modified configuration

During the search of the optimal configuration, to determine if a current modification of the configuration is accepted, an acceptance probability α is evaluated (for more details [38]). It integrates:

- Green Ratio [39] R_∞, that modulates acceptance according to the applied modification;
- the optimization function μ.

$\alpha = R_\infty \times min(1, e^{-\frac{\Delta E}{\mathcal{T}}}$ with $\Delta E = \mu C_{mod} - \mu C_{ini})$ and $\mathcal{T}$ temperature for current iteration described by a decreasing function.

The optimization function is a numerical function that traduces the characteristics of a good configuration for the constructor agent. Different functions may be used as the chosen optimization approach aims at being generic according to the hypothesis of use. The function is assessed on the whole configuration and may integrate different aspects or their combination:

- **Direct measure on a shape:** the optimization function can be directly measured on the shape and tend to maximize some aspects about it. For example, volume maximization may be applied to simulate the behavior of an agent that aims to optimize the benefits of its Right to Build;
- **Similarity to another shape:** the optimization process may be driven to look like an input shape in order to assess the possibility to build a such building. In this case, the optimization function is the similarity measure relatively to the input shape. Some complete reviews exist and present 2D [40] or in 3D [41] similarity measures. As some measures are not sensitive to rotation or scale changes [42, 43], the shape of a urban block or of aggregated buildings may be used as input;
- **Environmental factors:** Environmental indicators (solar irradiation, sky view factor, etc.) may be used in order to simulate a strategy for agent that integrates ecological aspects. This type of behavior may be used to estimate compromises between sustainability and city densification [1];

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- **Spatial pattern:** The optimization may also traduce the integration of urban configuration in existing pattern. The pattern may be based on indicator values distribution when several objects are generated (like height repartition in [44]) or by analyzing the different (simulated or existing) buildings [45].

5.6. Initialization and stop condition

In order to run the algorithm, some parameters have to be defined:

- **Initial configuration**: it can be empty or composed of boxes. The second case may be useful to refine a configuration by using another optimization function or an approximation of existing building that can be changed. The only condition is that the initial configuration have to respect the rules ;

- **Temperature decreasing function**: several methods exist to determine this function [38] and the initial temperature [46]. These elements are important as they define the number of configurations explored during the process and a good tuning allows to avoid local minima. In this work, we use a common geometric function proposed in [47]. For the iteration $it \in \mathbb{N}$, the temperature is: $\mathcal{T} = T_0 \tau^{it}$ avec $T_0 = \delta\mu$ where $\delta\mu$ is the maximum difference of value for the optimization function for two neighbour configurations ;

- **Stop condition**: the algorithm stop when a stability condition is checked *i.e.* when the best candidate is not improved by more than a given threshold value during a given number of iterations.

6. Experiment

We propose an implementation of the generation method (section 6.1). The first experiments aim to present the application of the method and to discuss parameters tuning (section 6.2). In a second experiment, the simulator is used

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with existing buildings and the generated configuration is composed of objects from another class (section 6.3). And finally, we present a potential use of the application in the context of regulation design (section 6.4).

6.1. Implementation

For the experiment, an implementation of our proposition is based on three open-source libraries:

- *GeOxygene3D*: a module of GeOxygene[11] platform dedicated to 3D GIS development. It is used for the implementation of our model, 3D operators and data integration [48];
- *librjmcmc4j*: a Java implementation of the *librjmcmc* library[12] [38] that provides generic mechanisms (sampling methods, temperature function, optimization function, etc.) to implement TDSA[13];
- *DresdenOCL*: that allows to generically manage (loading and checking) OCL constraints directly on Java classes[14] [49, 50].

The implementation of our proposition has been released in Open Source as three projects:

- SimPLU3D-rules [23]: it contains codes about geographic model definition (section 4.3), data integration and imports https://github.com/IGNF/simplu3D-rules;
- SimPLU3D-OCL, this project contains code about OCL rules management and rules checking https://github.com/IGNF/simplu3D-ocl;
- SimPLU3D: it encloses building generation process https://github.com/IGNF/simplu3D.

[11] Web site of GeOxygene project: http://oxygene-project.sourceforge.net/
[12] Web site of librjmcmc project: http://librjmcmc.ign.fr/
[13] Gith repository of librjmcmc4j library: https://github.com/IGNF/librjmcmc4j
[14] Web site of Dresden OCL project: http://www.dresden-ocl.org/index.php/DresdenOCL

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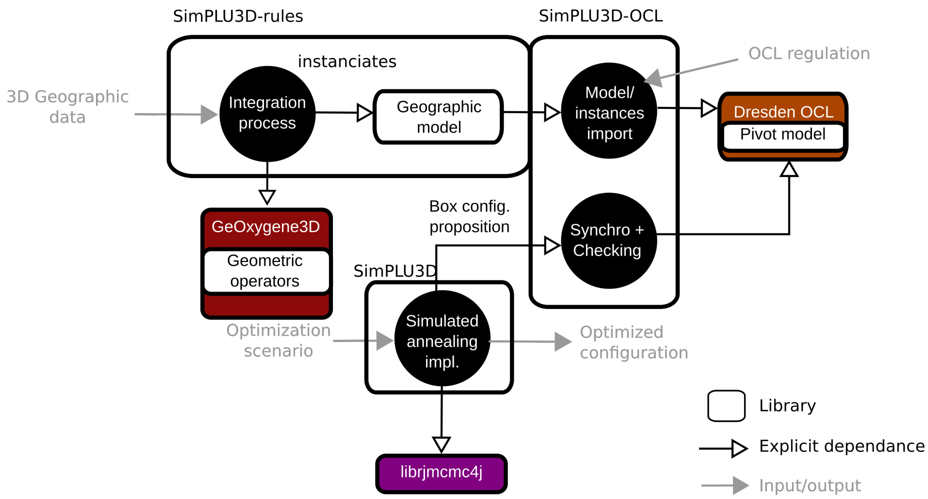

Figure 7: Architecture of the implemented prototype.

Figure 7 presents an overview of the architecture and the dependencies between the different mentioned libraries. The geographic model is implemented in the SimPLU3D-rules project according to its presentation in section 4.3. This model is instantiated through an integration process currently adapted to our experiment datasets (the integration process is described in [23]) that uses 3D geometric operators implemented in GeOxygene 3D. The SimPLU3D-OCL project allows the import of both model and instances in the DresdenOCL Pivot Model. In order to check OCL sentences, DresdenOCL is based on a generic meta-model that can integrate Java classes and objects. This import creates a copy of the geographic model into the DresdenOCL formalism. The simulated annealing process is instantiated according to the librjmcmc4j formalism. The implantation aims at defining the elements described in section 5. During the optimization process, box configurations are proposed according to the applied modifications. In order to check the respect of these configurations according to OCL sentences, the update of DresdenOCL instances is triggered in order to be synchronized with the state of the optimization process. A runnable test class

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can be found in the start page of the SimPLU3D-OCL project[15].

6.2. First simulation: typical example

The aim of this section is to present a first simulation example that describes the behaviour of our method and to discuss influences of the parameters. At first, the context of the simulation (section 6.2.1) and parameters are introduced (section 6.2.2). They produce a first simulation (section 6.2.3). We discuss about the parameters that influence significantly global the morphology of the configuration: space sampling of box dimensions (section 6.2.4), the influence of the parsimony term (section 6.2.5) and of the space reduction (section 6.2.6).

6.2.1. Context of the simulation

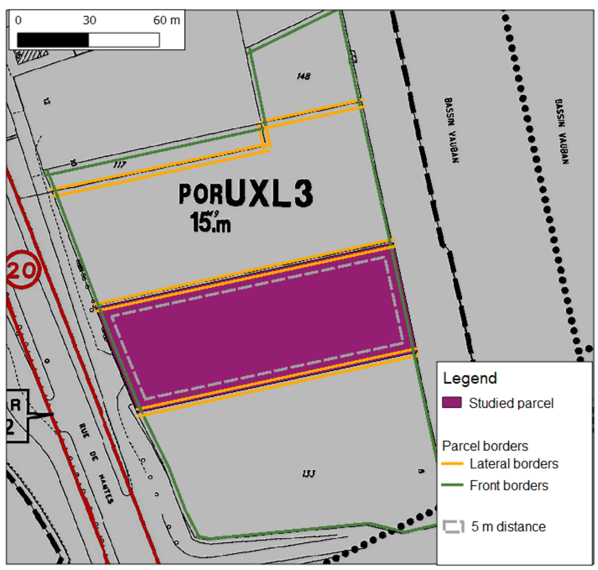

Figure 8: Aim-parcel with categorization of its borders.

The considered-parcel is located in an industrial zone of Strasbourg, France (in purple in figure 8) and constraints by a set of rules extracted from the local regulation [51]:

[15]https://github.com/IGNF/simplu3D-ocl

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Rule - 1 Buildings must be built with a minimum distance equals to 5 meters from existing or future public way;

Rule - 2 Horizontal distance between every point of the building and every point of the parcel border must be less than the difference of altitude between these two points;

Rule - 3 Distance between two non contiguous building must be less than 5 m;

Rule - 4 Building area cannot exceed 75 % of the parcel surface;

Rule - 5 Height measured from the average level of the neighbor road to the top of the building roof cannot exceed 15 m.

6.2.2. Standard parameterization of the algorithm

For this experiment, buildings are generated by a set of intersecting boxes. These boxes are sampled in a predefined search space:

- $5 \leq \mathrm{l} \leq 30$ m;
- $5 \leq \mathrm{w} \leq 30$ m;
- $2 \leq \mathrm{h} \leq 15$ m;
- $0 \leq \theta \leq \pi$.

Lower bound corresponds to minimal granularity of a box; higher bound is chosen to grant possibility to sample a box that totally overlaps the considered parcel.

Concerning the exploration of the search space, each proposition kernel has the same probability to be chosen. Displacement of a box is sampled between 0 and 2 m, modification of box dimensions between -2 m and 2 m and rotation between 0 and 10 ˚.

For the design of the optimization process, we suppose that the user is wondering: *"What happens if a builder tries to maximize its rights to build by constructing the biggest possible building?"*.

Thus, we propose to specify: $\mu = volume(configuration) + n_{boxes} \times E_{creation}$ where $n_{boxes} \times E_{creation}$ is a term that follows the principle of parsimony to avoid configurations with infinity of boxes that does not contribute significantly to improve the optimized configuration. In our function, $E_{creation}$ defines the minimal contribution of a box to be kept in the optimized configuration, *i.e.* in our case the minimal contribution of a box to the building volume. For this simulation, we choose $E_{creation} = 12m^3$ that is equivalent to a $2m \times 2m \times 3m$ box. This parameters also traduce the minimal granularity of the configuration optimized shape.

Concerning initialization, we set a start temperature $T_0 = 13500$ that corresponds to the biggest possible increase of μ with one modification of a configuration (the addition of a box with maximal dimension $30 \times 30 \times 15$). The stop condition is a stagnation criteria: the algorithm stops if the evaluation of the best candidate is not increased by more than 5 m^3 during 100 000 iterations.

6.2.3. First simulation

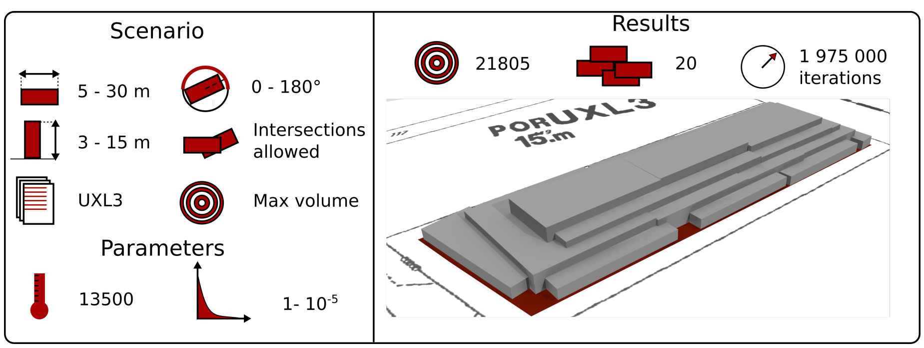

Figure 9: Result of a first simulation (in grey). For indication, a red polygon located at a distance of 5 m from borders is shown.

With these parameters, a first optimized configuration is presented in figure 9. The influence of the rules is clearly visible (notably rules 1 and 2) on the morphology of the optimized configuration. This configuration is not totally optimal, small parts of the polygon located at a 5 m distance from borders are still visible. This can be explained by two elements: due to parsimony term very

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small new boxes that cover these parts would not participate enough to improve the configuration and because current boxes reach the maximal dimension, their dimension cannot be increased any more.

A better optimization may be reached by modification of some parameters:

- a slower decrease of the temperature function results in a wider exploration of the search space;
- modification of box dimensions sampling (section 6.2.4);
- a lower parsimony term to allow boxes that contributes less significantly to the configuration (section 6.2.5);
- a stricter stop condition.

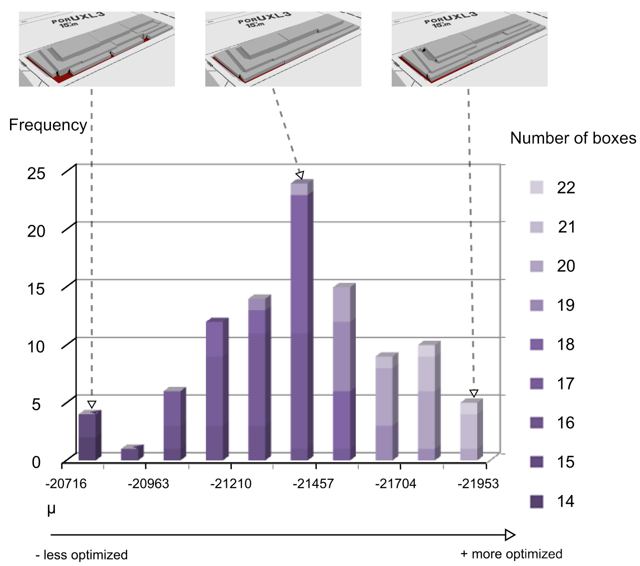

Figure 10: Distribution of 100 simulations (color corresponds to number of boxes). Average and extreme configurations are represented.

As the simulation process is stochastic, a way to evaluate its quality is to assess its stability. Figure 10 presents the distribution of 100 simulations. It is noticeable that there is only 5 % of difference between the worst configuration and the best. Thus, for this scenario, each simulation is quite close to the best

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configuration that the system can generate. The result validates the validity of the optimization process for this context. In an operatationnal context, it is advisable to proceed to such stability analysis on considered context in order to ensure the validity of chosen parameters.

6.2.4. Influence of box dimension

Box dimensions are sampled between a minimal and a maximal value that users have to define. To evaluate the influence of these parameters, ten simulations were produced with interval having 1, 5, 10 and 20 meters for minimal value and 30, 50, 75 and 100 meters for maximal value. Figure 11 synthesizes these results.

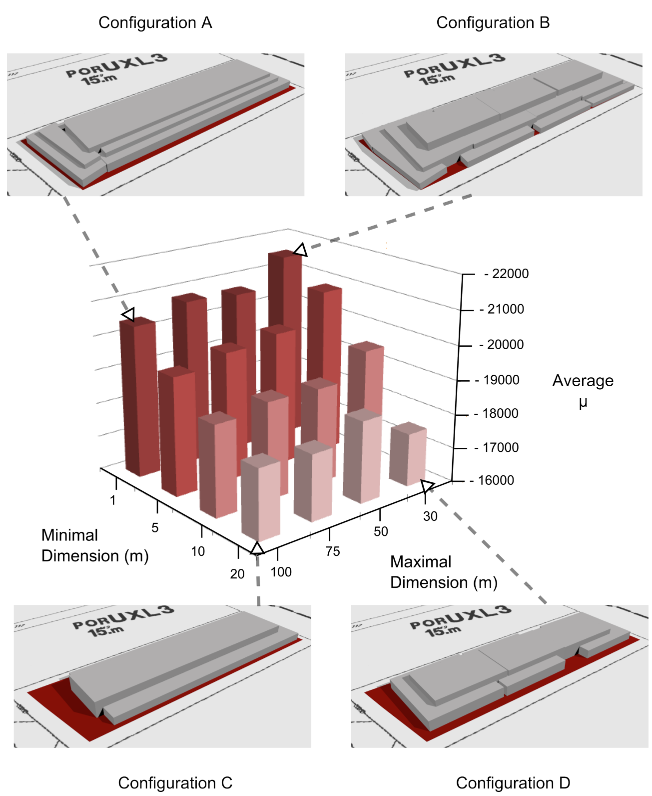

Figure 11: Average μ function for different interval for minimal and maximal box dimension. Extreme cases are represented.

Globally, we notice that configurations enabling smaller boxes are more optimized than the others. The size is very important as it allows covering small spaces of the parcel. This phenomenon is visible by comparing configurations A and C or configurations B and D. Without small boxes, the left part of the parcel is not filled. Higher maximal size causes a decrease of the number of boxes find in the solution; it is visible by comparing configurations A and B or configurations C and D and generates geometrically simplified configurations. Nevertheless, as it is more difficult for the system to plant big boxes, the set of relevant configurations explored decreases and so the effectiveness of the whole process. As the exploration space is wider, a more important number of iterations is required to preserve the quality of the optimized solution.

6.2.5. Influence of parsimony term $E_{creation}$

Figure 12 presents the evolution of μ with $E_{creation}$ for ten simulations. μ increases with $E_{creation}$, this can be explained by the fact that only boxes with high contribution for the optimized configuration are kept. It is visible in the different represented solutions. Thus, $E_{creation}$ is an other parameter that decreases the granularity of the optimized configurations. For $E_{creation} = 1$, better configurations than the one with standard parameters are provided and the allowed volume of the parcel is better filled.

6.2.6. Influence of search space reduction

This experiment aims to show the interest and the limit of search space reduction on the quality of the simulation process. The space reduction may be determined when prior knowledge is available on the regulation, notably, when zones in which the boxes cannot be built can be determined from a parcel. For this experiment, it is possible to determine the forbidden zone of the parcel where the sampling of a box center will always lead to the non-respect of this rule by using Rule 3. This forbidden zone is here determined by processing a negative buffer of $7.5m$ (value of the rule + value of the minimal width of a box) on the whole parcel. Thus, processing the optimization with the space

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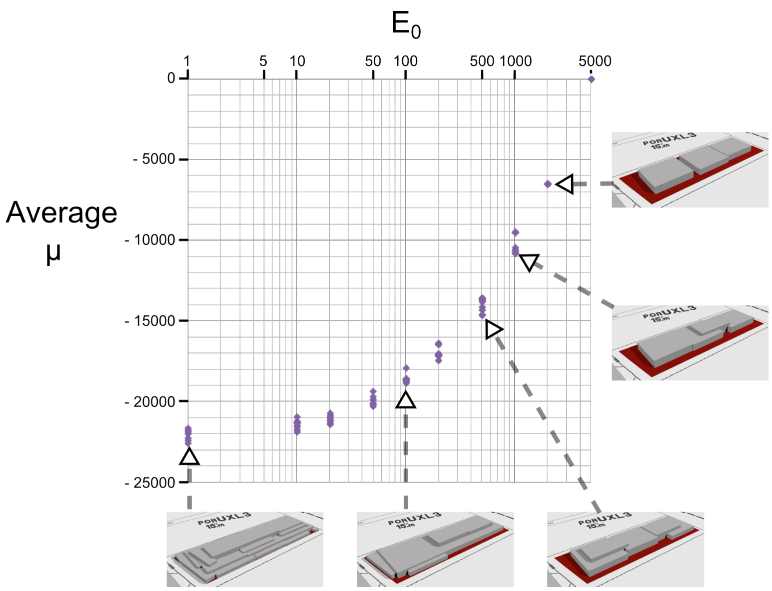

Figure 12: Evolution for ten simulation of the average μ with $E_creation$ evolution.

optimization method consists in sampling the center in the difference between the parcel geometry and the forbidden zone geometry.

In order to test the influence of this search space reduction on the simulation, 100 simulations are processed and a set of indicators are collected: the energy of the resulting configuration, the percentage of success in rules checking and the execution time. The results are presented in table 2.

Space reduction	Energy	Success (%)	Time (ms)
Without	-20402.942	0.449	37123.8
With	-20506.456	0.45	36657.66

Table 2: Average values for 100 simulations with or without space reduction.

The results show a small reduction of time execution (1 second per simulation) and no important evolution for the average energy (around 0.5 %). The increase of the success ratio is very weak as this space reduction only guarantees that a box with minimal dimensions respects the $5m$ rules. During the

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optimization process, configurations that do not respect this rule will be continuously evaluated. That is why, there is no significant decrease of the success value. The results may be more interesting in more constrained configurations but they show the difficulty to choose an efficient space reduction strategy for the problem. A more restricted sampling area may imply a decrease in the quality of the optimized configurations.

6.3. Urban densification simulation

The aim of this experiment is to use SimPLU3D approach in the context of urban simulation densification. In this section, the simulation is performed by considering existing buildings (modelled from a CityGML LOD2 dataset) that constraint the simulated building configurations. Furthermore, in order to highlight the genericity of the method, another type of parametric object is used: L-shape buildings with parametric roofs. The considered zone is a set of residential parcels located in Strasbourg, France (figure 13).

6.3.1. Rules

The regulation is based on zone UB16 [51]:

Rule - 1 Building parts must be built at a certain distance from bottom separative limits according to the distance to the road as follow:

- if the distance is lesser than $13m$, the distance to separative limits must be higher than $1.9m$;
- if the distance is between $13m$ and $20m$, the distance to separative limits must be higher than $3m$;
- if the distance is higher than $20m$, the distance to separative limits must be higher than $6m$.

Rule - 2 The distance between buildings must be higher than $5m$;

Rule - 3 The height of new buildings must be lesser than distance to existing buildings ;

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Figure 13: Parcels of the experiment with the categorization of their borders and the existing buildings.

Rule - 4 The distance between new buildings and road borders must be higher than $1.5m$;

Rule - 5 Maximal height is $15m$.

For this experiment, existing buildings are modelled using a CityGML LOD2 dataset that can be directly loaded into SimPLU3D. It is directly possible to check the OCL sentences on all the loaded objects. Thus, rules 2 and 3 are considered between simulated and existing buildings or between simulated buildings and are so particularly relevant for this experiment.

6.3.2. Parametric shapes and results

The geometric shape used and the simulation results are presented in figure 14. SimPLU3D generates L-shape buildings with typified roof. Each building is described through 8 dimensions:

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- Five for the footprint: width and length for the two bars of the L and general orientation of the building;
- Three dimensions for the roof: height to gutter, height between gutter and top and a value between 0 et 1 that describes the slope of the gables[16].

During the optimization process, the simulator also determines the optimized roof shape. Changing the type of parametric shape in SimPLU3D is not a complex task as it only requires (1) to define a class that uses these parameters, (2) to implement a method that allows the generation of 3D and footprint geometry from these parameters and (3) to set the explored value intervals for these parameters.

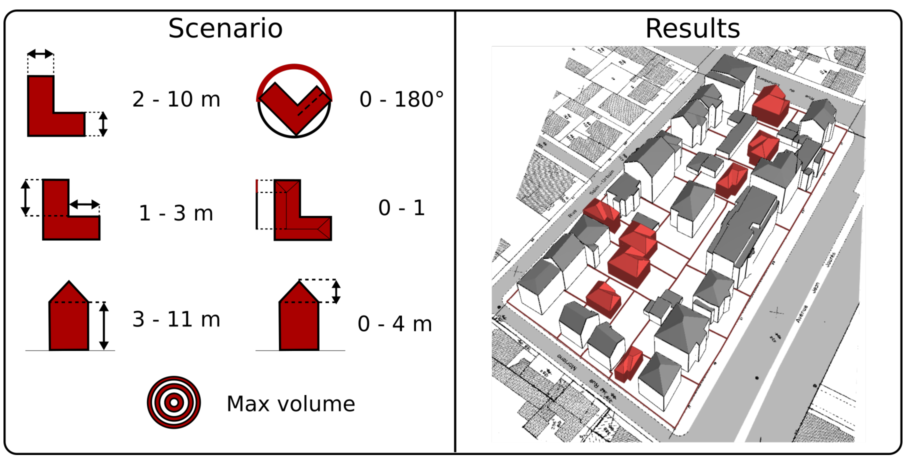

Figure 14: Interval values for the chosen parametric shape and simulation result. Existing buildings are colored in grey and white and simulated buildings are colored in red.

As a result, the system proposes a set of new possible buildings. When a parcel is already built, the system generates zero or one building according to the allowed constructions. Nevertheless, we may notice that the system adds two building on a non-built parcel as the system determines the optimized number of buildings. This kind of experiment is interesting when trying to

[16]If the value is zero, the gable is vertical, when the value is one the top of the two gables are intersecting.

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simulate a BIMBY approach[17]. It may be an interesting material to discuss with citizen in order to motivate them to adopt this approach. However, to be completely operational in this context, SimPLU3D has to integrate some other types of densification processes. This may be performed in the future by handling different classes of objects (new buildings, floor additions and building extensions). Optimization with several classes of objects is available in our optimization library (librjmcmc4j) but this concept is not currently derived for building configuration simulation.

6.4. Use of the method for regulation design

The aim of this experiment is to present a use case where a LUPS designer is trying to fix rules parameters to optimize his goals. For this experiment existing buildings are removed (figure 13) and standard parametrization of the first experiment is used.

6.4.1. Rules

For this experiment we consider a user that tries to fix the parameters of a rule considering a set of other predefined rules.

Considered parametric rule is a prospect rule with two parameters named initial height H_{ini} and slope s. Its textual form is: "*Horizontal distance multiplied by s between every point of the building and every point of lateral and bottom parcel border*[18] *plus H_{ini} must be less than the difference of altitude between these two points.*". This rule is represented in figure 15 and constraints all points p of buildings to stay under the plan defined from each relevant border b by the equation: $P(b) = s \times distance(b, p) + H_{ini}$.

The set of predefined rules used in our experiments is extracted from Strasbourg local regulation [51] and is summarized here with their corresponding number of article:

[17] As mentioned here: https://www.bimby.org.uk/

[18] In red and grey in figure 13.

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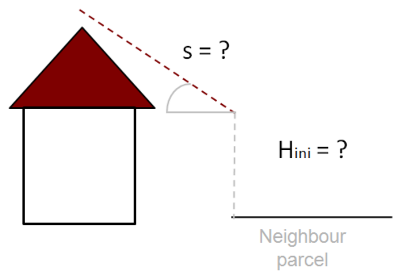

Figure 15: Illustration of prospect rules with its parameters.

Rule - 1 Buildings must be built with a minimum distance equal to 1.5 meters from existing or future public way or easement;

Rule - 2 Distance between two non contiguous building must be smaller than 5 m;

Rule - 3 Building area cannot exceed 50 % of the parcel surface;

Rule - 4 Height measured from the average level of the neighbour road to the top of the building roof cannot exceed 12 m.

6.4.2. Simulation

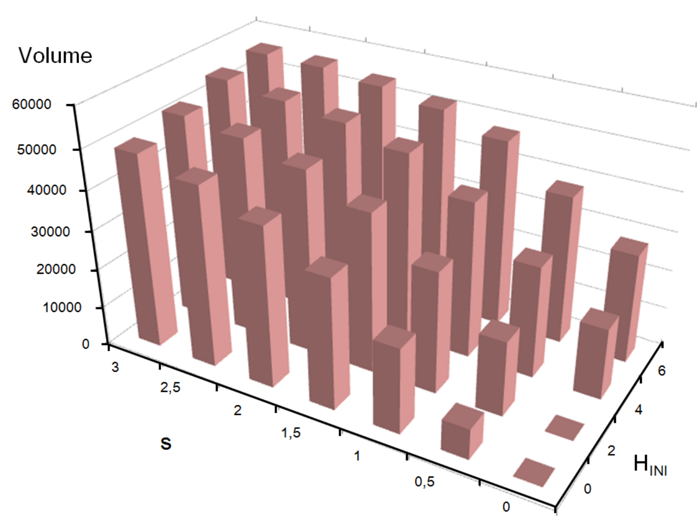

Figure 16: Variation of average volume for different values of H_{ini} and s for ten simulations.

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To assess the influence of the parameters on the zone, we proceed to ten simulations for each couple of values with parameters $H_{ini} \in \{0, 2, 4, 6\}$ and $s \in \{0, 0.5, 1, 1.5, 2, 2.5, 3\}$. Figure 16 presents the average volume values.

Globally, we notice that results are conforming with the intuition: average volume increases with parameters values. The prospect rule is less limiting with higher parameter values and allows more voluminous buildings. More locally, for the lowest values, there is no construction proposed by the simulation for the set of parcels. By increasing parameters, more and more parcels become buildable for the system. For example, for $H_{ini} = 2$ and $s = 0.5$, each parcel but one has at least one building. For higher values, a reduction in volume increase is visible: with an important slope ($s = 3$) and initial height (H_{ini} $= 3$), the prospect rules does not constraint anymore the height of proposed buildings that is limited to 12 m in the fixed rules. It provides information for the heighest values, this rule is useless and do not have to appear in a final regulation. These results provide an evaluation of possible volumes according to these parameters to the designer. This graphic helps him to determine the influence of indicators and when a rule prevents new constructions or does not add supplementary constraints.

Table 3 shows some configurations produced during the simulations. The impact of the different parameters is significant not only on the volume but also on the shape of generated configurations. With low initial height, buildings are recoiled from parcel borders because minimal height of boxes is 2 m. Configuration with parameters $H_{ini} = 6$ and $s = 3$ presents buildings with exactly the same height: 12 m. That confirms observations from the previous graphics: even by increasing the values of the prospect parameters, it is not possible to build more voluminous buildings.

Thanks to these results, a designer may choose between different urban configurations according to urban fabric characteristics (for example: presence of cavities). They offer several options and provide visual support to inform discussions about the definition of new regulations.

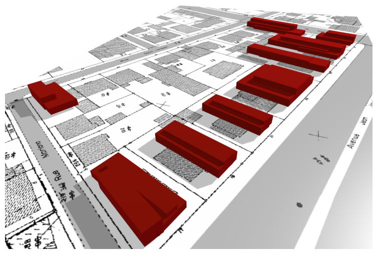
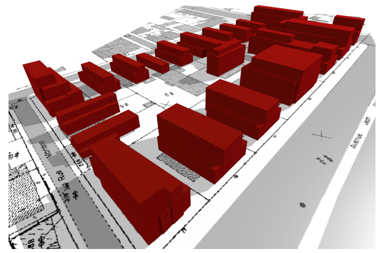
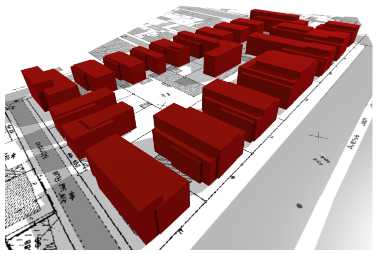
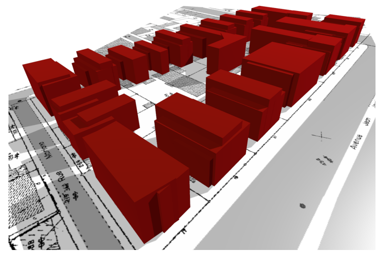
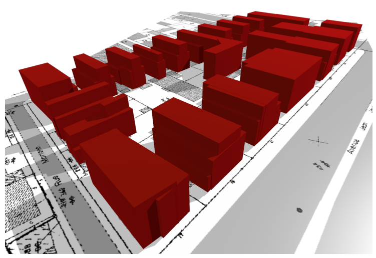
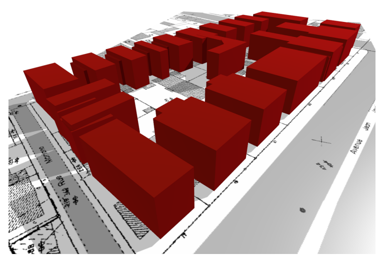
	$H_{ini} = 0m$	$H_{ini} = 6m$
$s = 0.5$		
$s = 1.5$		
$s = 3$		

Table 3: Different building configurations according to parameters values.

7. Conclusion

In this paper, we present a method to simulate 3D buildings using a TDSA process constrained by a generic OCL rule checker. We propose the specification and the organization of regulation knowledge through a model formalizing spatial knowledge contained in French local urban regulation. This model is built by linking together several existing geographic standards. The OCL language ensures a generic formalization of rules and possibilities of extension. We introduce a method to generate buildings as a set of parametric objects. The generation requires an optimization function to describe the goal characteristics of the buildings. We present an implementation of our method based on the

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rejection of configurations that do not respect rules and apply it on a simple simulation to discuss the influence of parameters. At the end, we show a potential application of this method to help a designer to fix the parameters of a regulation by exploring its influence on the buildings that can be potentially built. This application may assist local administration to asses the influence of a LUPS modification on a large territory or to help citizen to asses the constructibility of a parcel without juridic or architectural expert assessment.

Some improvements can be added concerning rule formulation. Currently, only simple and factual rule elements are taken into account. It would be challenging to design and to integrate more complex practices (for example: the respect of urban rhythm) both in the model and in rule evaluation. Applications dedicated to architects or building promoters may be designed on the principle of the presented method. The architect may set some parameters (for example, the height of a building, the floor area, etc.) and the system determines the best position according to some external criterion (such as solar energy or visibility accessibility) in order to improve the quality of a pre-defined project. Such applications may also include the handling of architectural elements such as balconies or windows by considering multi-object optimization. One important step to manage this use case is the integration of architectural model (in CAD or BIM formats). Some propositions aim at easing this conversion notably in the Future City Pilot project[19]. In this project, GeoBIM standard is used in order to ease rule checking for architectural project. This approach makes the integration of such data into SimPLU3D theoretically possible.

Another interesting improvement would be to automatically rewrite some rules to avoid specific difficulties mentioned in section 5.4. For instance, by detecting logical elements that cause disjunction or elements of rules with strict constraints, it may be possible to split one rule on sub-rules to ensure a simpler search space. A second possibility is to change rule management and to penalize optimization function according to the probability that a building respect a rule

[19]http://www.opengeospatial.org/projects/initiatives/fcp1

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or not. This option is less generic for rule expression than ours but may ease the exploration of search space. A first treatment of these aspects is presented in another work [52].

About the optimization process, several improvements could be made. To begin with, it should be interesting to take into account several other types of objects. Local regulations can demand the creation of a parking according to new project dimensions or the creation of green space. By integrating these elements of regulation, the system may influence dimensions of created buildings.

We only consider mono-objective optimization, but are currently working on multi-objective simulation in order to generate building configurations according to different incompatible indicators (for example, environment vs density). We aim at allowing the exploration of the variety of possible configuration according to different compromises in term of indicators by using the Pattern Search Exploration (PSE) method [53].

Another important aspect is the integration of data accuracy in the optimization function. The optimization process is led by the fact that two configurations can be compared. With data accuracy management, it is necessary to use advanced methods to ensure that a solution is better than another one and this is not a side effect due to data accuracy. For example, [54] proposes a probabilistic approach in simulated annealing for such an assessment.

For long term work, we expect two uses of such an application. The first one is urban evolution simulation in order to assess how a new plan will affect a city and to check if past plans were effective. We are aiming at coupling the model with the MUP-City simulator [55] that defines zones that are likely to be built according to urban planning scenarios. This kind of coupling allows to check if local constructability allows to reach the objectives defined in the urban planning scenarios. Furthermore, we may imagine some other possible couplings notably with other phenomena, for instance, to orchestrate constructor agent strategies or to integrate city evolution.

A second and last idea is to connect our simulator to another optimization process with the aim to automatically find the best rule parameters that optimize a set of expected indicators values (sky view factor, visibility access to a lake, solar irradiation on a zone). Some preliminary works about this issue are introduced in [56]. This subject leads to consider the more global question of having 3D GIS that better integrate knowledge about a city.

8. Acknowledgment

This work was partly funded by the *e-PLU* FEDER project and the Île-De-France Region. We also express our gratitude to the Urban Community of Strasbourg for providing us databases in the context of the ZAEU agreement (Urban Environmental Study Zone).

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