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Building Information Modeling Using Constraint Logic Programming[*]

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Abstract

Building Information Modeling (BIM) produces three-dimensional object-oriented models of buildings combining the geometrical information with a wide range of properties about materials, products, safety, to name just a few. BIM is slowly but inevitably revolutionizing the architecture, engineering, and construction industry. Buildings need to be compliant with regulations about stability, safety, and environmental impact. Manual compliance checking is tedious and error-prone, and amending flaws discovered only at construction time causes huge additional costs and delays. Several tools can check BIM models for conformance with rules/guidelines. For example, Singapore's CORENET e-Submission System checks fire safety. But since the current BIM exchange format only contains basic information about building objects, a separate, ad-hoc model pre-processing is required to determine, for example, evacuation routes. Moreover, they face difficulties in adapting existing built-in rules and/or adding new ones (to cater for building regulations, that can vary not only among countries but also among parts of the same city), if at all possible. We propose the use of logic-based executable formalisms (CLP and Constraint ASP) to couple BIM models with advanced knowledge representation and reasoning capabilities. Previous experience shows that such formalisms can be used to uniformly capture and reason with knowledge (including ambiguity) in a large variety of domains. Additionally, incorporating checking within design tools makes it possible to ensure that models are rule-compliant at every step. This also prevents erroneous designs from having to be (partially) redone, which is also costly and burdensome. To validate our proposal, we implemented a preliminary reasoner under CLP(Q/R) and ASP with constraints and evaluated it with several BIM models.

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1 Introduction

Building Information Modeling is a digital technology that is changing the Architecture, Engineering, and Construction industry. It combines the three-dimensional geometry with non-geometrical information of a building in an object-oriented model that can be shared among actors over the construction lifecycle. To facilitate the exchange of BIM models, BuildingSMART (2020) has developed Industry Foundation Classes (IFC), an open, vendor-neutral exchange format.

Since 2016, the UK Government has required the Level 2 of BIM maturity for any public construction project, where each discipline generates specific models following the BIM standard. Once these specific models are built, an Automated Code Compliance Checking tool, for example, BIM's Solibry Model Checker (SMC), provides basic architectural checks, to verify the completeness of information and detect the intersection of building components, among other things. Additionally, automated tools check models in IFC format for conformance with specifications, codes, and/or guidelines. For example, the CORENET BIM e-Submission by Singapore Government (2016) can be used to check fire safety. However, since the IFC format only represents basic building objects and static information of their properties, pre-processing of the model is required to, for example, determine evacuation routes. Moreover, these tools offer limited scope for customization or flexibility and it is not easy to modify the implemented rules and/or create new ones.

The domain of construction modeling needs several capabilities: geometrical reasoning (including arithmetical/mathematical capabilities and qualitative position knowledge), reasoning about symbolic/conceptual knowledge, and reasoning in the presence of vague concepts and/or incomplete information (e.g. whether or not the outdoor space is safe depends on details that are not yet known at this level of the design). In addition, since part of the reasoning involves regulatory codes and standards, a certain degree of ambiguity and discretionary decisions are expected.

Interestingly, these different types of reasoning are not layered: a model cannot be validated by first checking structural integrity (i.e. that walls do not overlap or that columns are not placed where a door is expected to be placed), then positional reasoning, and then legal compliance. Legal requirements in this domain include restrictions on sizes, areas, distances, relative positions, etc. Therefore, a formalism suitable for checking (and, if executable, for generating alternative models) has to be able to seamlessly capture (and reason with) all of these types of information simultaneously. Moreover, since regulations differ not only between countries, but also among states/regions within a country, they must be easy to write and, since they also change in time, to modify.

We believe that a formalism based on logic programming can meet many, if not all, of the above requirements: a successful answer to a query can determine that a model meets all the requirements. Different answers (or models) to a query may give alternative designs that satisfy the requirements. There exist query languages for BIM, such as BimSPARQL, by Zhang *et al.* (2018), and several logic-based proposals, for example, by

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Pauwels *et al.* (2011), Zhang *et al.* (2013), Solihin (2015), Lee *et al.* (2016), and Li *et al.* (2020), that validate our approach because they show that minimal proof-of-concept tools have improved reasoning capabilities w.r.t. commercial off-the-shelf BIM Software. However, they all report limitations in the representation of geometrical information and/or in the flexibility of the proposal to adapt the code and/or the evaluation engine for different scenarios.

We propose to use tools integrating Constraint Logic Programming with ASP to model dynamic information and restrictions in BIM models and to enable the use of logic-based methodologies such as model refinement. The main contributions of this paper are:

- A library, based on Constraint Answer Set Programming (CASP), that allows unified representation of geometrical and non-geometrical information.
- The prototype of a preliminary 3D reasoner under Prolog with CLP(Q/R) that we evaluate with several BIM models.
- The outline of an alternative implementation of this spatial reasoner under CASP, using s(CASP), by Arias *et al.* (2018), a goal-directed implementation of CASP.
- Evidence for the benefits of using s(CASP) in BIM model evaluation: (i) it has the *relevance* property, (ii) it can generate justifications for negative queries, and (iii) it makes representing and reasoning with ambiguities easier.

The ultimate goal of this work is to shift from BIM verification to BIM refinement and to facilitate the implementation of new specifications, construction standards, etc.

2 Background

This section briefly describes (i) Building Information Modeling (BIM), (ii) the industry foundation classes (IFC), a standard for openBIM data exchange, and (iii) s(CASP), a goal-directed implementation of CASP.

2.1 BIM + IFC

Building information modeling (BIM) has evolved from object-based parametric 3D modeling. Combining geometrical information with other properties (costs, materials, process, etc.) makes it possible to have a range of new functionalities, including cost estimations, quantity takeoffs, or energy analysis. The goal of BIM is to achieve a consistent and continuous use of digital information throughout the entire life cycle of a facility, including its design, construction, and operation. BIM is based on a digital model and intends to raise productivity while lowering error rates, as mistakes can be detected and resolved before they become serious problems during construction and/or operation. The most important advantages lie in the direct use of analysis and simulation tools on these models and the seamless transfer of data for the operation phase. Today, there are numerous BIM authoring tools, such as Revit, ArchiCAD, Tekla Structures, or Allplan, that provide the basics for realizing BIM-based construction projects.

BuildingSMART (2020) has developed BIM interoperability technologies, the most important of which is IFC (Industry Foundation Classes), a common data model for representing buildings. IFC is standardized as ISO 16739 to improve BIM data interoperability between heterogeneous BIM authoring tools and applications in their disciplines.

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The IFC schema is an extensive data model that logically encodes (i) the identity and semantics (name, identifier, type), (ii) the characteristics or attributes (material, color, thermal properties), and (iii) the relationships (including locations, connections, and ownership) of (a) objects (doors, beams), (b) abstract concepts (performance, costing), (c) processes (installation, operations), and (d) people (owners, designers, contractors, suppliers). For example, the IFC label *IfcBeam* is used to identify the beams (part of the structure of a building that supports heavyweight).

IFC allows describing how a facility is designed, how it can be constructed, and how its systems will function. It defines building components, manufactured products, mechanical/electrical systems, as well as more abstract models for structural analysis, energy analysis, cost breakdowns, work schedules, etc. IFC is in development since 1994 and now specifies close to one thousand different entity types. IFC 4.0.1.2 was approved as ISO standard 16739 in 2017. The specification of IFC5 is currently in progress.

2.2 s(CASP)

s(CASP), presented by Arias *et al.* (2018), extends the expressiveness of Answer Set Programming systems, based on the stable model semantics by Gelfond and Lifschitz (1988), by including predicates, constraints among non-ground variables, uninterpreted functions, and, most importantly, a top-down, query-driven execution strategy. These features make it possible to return answers with non-ground variables (possibly including constraints among them) and to compute partial models by returning only the fragment of a stable model that is necessary to support the answer to a given query.

In s(CASP), thanks to the constructive negation, `not p(X)` can return bindings for `X` for which the call `p(X)` would have failed. Additionally, thanks to the interface of s(CASP) with constraint solvers, sound non-monotonic reasoning with constraints is possible. s(CASP), like other ASP implementations and unlike Prolog, handles non-stratified negation.

Example 1. Consider the program `size(r1,S):- S#>=21` (see size.pl), For the query `?- not size(r1,S)`, s(CASP) returns the model `{not size(r1,S | {S #< 21})}`.

Example 2. The following program, in kitchen.pl, models that the room `r1` is either small or big and it is a kitchen:

```
1 small(r1) :- not big(r1).
2 big(r1) :- not small(r1).
3 kitchen(r1).
```

The top-down evaluation of the non-stratified negation in lines 1-2 detects a loop having an even number of intervening negations (and *even loop*). When this is discovered, the truth/falsehood of the atoms involved is guessed to generate different models whose consistency is subsequently checked. In this example, there are two possible models, and given a query it returns the *relevant* partial model (if it exists):

```
?- small(r1).                    returns {small(r1), not big(r1)}
?- big(r1).                      returns {big(r1), not small(r1)}
?- kitchen(r1).                        returns {kitchen(r1)}
?- big(r1), small(r1).                    returns no models
```

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In addition to default negation, s(CASP) supports classical negation, marked with the prefix "-," to capture the explicit evidence that a literal is false: `not small(r1)` expresses that we have no evidence that `r1` is small (we cannot prove it), and `-small(r1)` means that we have *explicit* evidence (there is proof) that `r1` is not small.

Finally, s(CASP) provides a mechanism to present justifications in natural language. Both plain text and user-friendly, expandable HTML can be generated (e.g. small_r1.txt and small_r1.html show the justification for the query `?- small(r1)` in Example 2).

3 Modeling vague concepts

We present now a proposal to represent vague concepts using s(CASP). The formal representation of legal norms to automate reasoning and/or check compliance is well known in the literature. There are several proposals for deterministic rules. However, none of the existing proposals, based on Prolog or standard ASP, can efficiently represent vague concepts due to unknown information, ambiguity, and/or administrative discretion.

Example 3. Considering the following norm from a building regulation:

> In the room there is at least one window, and each window must be wider than 0.60 m. If the room is small, it can be between 0.50 and 0.60 m wide.

We can encode this norm using default negation:

```
1 requirement_a(Room):- window_belongs(Window,Room), width(Window,Width),
2                       Width #> 0.60, not small(Room).
3 requirement_a(Room):- window_belongs(Window,Room), width(Window,Width),
4                       Width #> 0.50, small(Room).
```

However, without information on the size of the room or what is the criteria to consider that a room is small, it is not possible to determine whether the room is small and only the first rule would succeed.

To encode the absence of information we propose the use of the stable model semantics by Gelfond and Lifschitz (1988), which makes it possible to reason about various scenarios simultaneously, for example, in the previous example we can consider two scenarios (models): in one a given room is small and in the other, it is not.

Example 4 (Example 3 (cont.)). Figure 1 models a hotel with eight rooms, for which we only know the size of three (lines 1-3). Following the patterns by Arias *et al.* (2021), lines 8-9 make it possible to reason considering (i) unknown information (size of rooms $r4$ to $r8$), and/or (ii) vague concepts: line 5 states that a room smaller than 10 m^2 is small and line 6 states that a room larger than 20 m^2 is not small. However, it is not clear whether rooms with size between 10 and 20 m^2 are small or not. Line 8 captures that there is evidence that the room is small, line 9 captures the case when there is an explicit evidence (there is proof) that the room is not small, and lines 10-11 generate two possible models otherwise. Finally, `room_is/2` determines whether a room is small or not based on evidence and/or assumptions: for room $r1$ the query `?-room_is(r1,Size)` returns `S=big`, for $r2$ it returns `S=small`, and for the other rooms it returns both alternatives: `S=small` assuming that `small(r3)` holds and `S=big` assuming that `-small(r3)` holds.

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```
room(r1).      room(r2).      room(r3).      room(r4).
room(r5).      room(r6).      room(r7).      room(r8).
size(r1, 25).        size(r2, 5).        size(r3, 15).

evidence(Room, small) :- size(Room,Size), Size #< 10.
-evidence(Room, small) :- size(Room,Size), Size #> 20.

small(Room) :- evidence(Room,small).
-small(Room) :- -evidence(Room,small).
small(Room) :- not evidence(Room,small), not -small(Room).
-small(Room) :- not -evidence(Room,small), not small(Room).

room_is(Room,big) :- room(Room), -small(Room).
room_is(Room,small) :- room(Room), small(Room).
```

Fig. 1. Code representing vague and unknown information (available at room.pl).

4 Modeling and manipulating 3D objects

We will now describe our proposal to model and manipulate geometrical information used to represent 3D objects which will be used to model buildings, infrastructures, etc. using constraints. Additionally, we show how the operations that manipulate these objects can also be used to infer new knowledge and/or to verify that geometrical data and non-geometrical information are consistent at each stage of the project development.

4.1 Representing 3D objects using linear equations

Any 3D object can be approximated as the union of convex shapes. The simplest shape to represent with linear equations is a box with edges parallel to the axes of coordinates. Assuming that P_a and P_b are opposing vertices with P_a being the one closest to the coordinate origin, the box is a set of points P with coordinates (X, Y, Z) (resp. (X_a, Y_a, Z_a) for P_a and similarly for P_b) such that

$$X \geq X_a \wedge X < X_b \wedge Y \geq Y_a \wedge Y < Y_b \wedge Z \geq Z_a \wedge Z < Z_b$$

Equations of this type can be easily managed using a simple linear constraint solver. In this paper, we use the well-known CLP(Q) solver by Holzbaur (1995)[1] and we represent such an object with the term `point(X, Y, Z)` where `X`, `Y`, and `Z` are variables adequately constrained as shown before. When a complex object has to be decomposed into convex shapes S_i, we define this object as the set of points P such that $P \in S_1 \vee P \in S_2 \vee \cdots \vee P \in S_n$. Since CLP(Q) does not provide logical disjunction as part of the constraint solver's operations, we explicitly represent the union of objects as a list of convex shapes `[convex(Vars_1), convex(Vars_2), ...]`, where `Vars_x` encodes the variables that carry the constraints corresponding to the linear equations of each S_i.

Example 5. A 3D box whose defining vertices are P_a and P_b (represented, resp. as `point(Xa,Ya,Za)` and `point(Xb,Yb,Zb)`), is encoded as:

[1] We use a constraint solver over rationals to avoid the loss of precision associated with the use of reals.

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```
box(point(Xa,Ya,Za), point(Xb,Yb,Zb), [convex([X,Y,Z])]) :-
    X #>= Xa, X #< Xb, Y #>= Ya, Y #< Yb, Z #>= Za, Z #< Zb.
```

where the box is represented with a list that contains a single convex shape.

Most objects in the definition of a building are extruded 2D convex polygons, and therefore having an explicit operation for this case is useful and it illustrates the power of using CLP for modeling building structures.

Example 6. Given a 3D object defined by its base (a convex polygon determined by its vertices $A, B, C, \ldots$ in clockwise order) and its height H, its representation is:

```
poly_extrude(Vertices, H, [convex([X,Y,Z])]) :-
    Vertices = [point(_,_,Za), _, _ | _],     % At least three points
    polygon(Vertices,[X,Y]), Z #>= Za, Z #< Za+H.
polygon([_], _).
polygon([point(Xa,Ya,_), point(Xb,Yb,_) | Vs], [X,Y]) :-
     (Xb-Xa) * (Y-Ya) - (X-Xa) * (Yb-Ya)  #=< 0,
     polygon([point(Xb,Yb,_) | Vs], [X,Y]).
```

4.2 Operations on n-dimensional objects under CLP(Q)

In this section, we explain some basic operations (union, intersection, complement, and subtraction) to manipulate the 3D objects that describe the BIM project. Figure 2 shows a preliminary interface implemented using CLP(Q) with the following four predicates that can be used to manipulate shapes in any n-dimensional space:[2]

- `shape_union(ShA, ShB, Union)`: Given two shapes ShA and ShB, it creates a new shape $Union$ that is the union, that is, $Union = ShA \cup ShB$. Since every shape is, in general, the union of simpler convex shapes (represented as a list thereof), $Union$ can simply be represented as a list containing the convex shapes of ShA and ShB (line 2). Simplification (to, e.g. remove shapes contained inside other shapes) can be done, but we have not shown it here for simplicity.
- `shape_intersect(ShA, ShB, Intersection)`: Given two shapes ShA and ShB, it creates a new shape $Intersection$ which is the intersection, that is, $Intersection = ShA \cap ShB$ (lines 5-6). This is computed with the union of the pairwise intersections of the shapes in ShA and ShB. Obtaining the intersection of two convex shapes is done by the CLP(Q) constraint solver, which determines the set of points that are in both shapes as those which satisfy the constraints of both shapes. In line 15, `copy_term/2` preserves the variables by generating a new set, `VarInt`.[3]
- `shape_complement(ShA, Complement)`: Given a shape ShA, it creates a new shape $Complement$ that contains every point in the n-dimensional space that is not in the shape ShA (lines 20-25). This is computed as the dual of ShA. From a logical point of view, it corresponds to the negation, so it is denoted as $Complement = \neg\, ShA$.

[2] We assume that union, intersection, etc. of shapes is understood as the corresponding operations on the sets of points contained inside the shapes.

[3] In line 15, `true` is needed due to a well-known, subtle bug in the implementation of attributed variables of the underlying Prolog infrastructure used in this paper.

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```
% Union = ShA ∪ ShB
shape_union(ShA, ShB, Union) :- append(ShA, ShB, Union).

% Intersection = ShA ∩ ShB
shape_intersect(ShA, ShB, Intersection) :-
    shape_intersect_(ShA, ShB, [], Intersection).
shape_intersect_([],_,ShInt,ShInt) :- !.
shape_intersect_(_,[],ShInt,ShInt) :- !.
shape_intersect_([Sh1|Sh1s],[Sh2|Sh2s],ShInt0,ShInt) :-
    convex_intersect(Sh1, Sh2, Sh12),
    shape_union(ShInt0,Sh12,ShInt1),
    shape_intersect_([Sh1], Sh2s, ShInt1,ShInt2),
    shape_intersect_(Sh1s,[Sh2|Sh2s],ShInt2,ShInt).
convex_intersect(convex(Vars1),convex(Vars2),ShInt) :-
    (   copy_term(Vars1,VarInt), copy_term(Vars2,VarInt), true ->
        ShInt = [convex(VarInt)]
    ;   ShInt = []                ).

% Complement = ¬ ShA
shape_complement([], [convex(_)]).
shape_complement([convex(Vars)], NotSh) :-
    findall(convex(DualVars), dual_vars_clp(Vars, DualVars), NotSh).
dual_vars_clp(Vars, TempVars) :-
    dump_clp_constraints(Vars,TempVars,TempGeo), TempGeo \= [],
    dual_clp(TempGeo,Dual), apply_clp_constraints(Dual).

% Subtract = ShA ∩ ¬ ShB
shape_subtract([],_,[]) :- !.
shape_subtract(ShA,[],ShA) :- !.
shape_subtract([Sh1|Sh1s],ShB, Sh1Remains) :-
    convex_subtract(Sh1,ShB,Remain0),
    shape_subtract(Sh1s,ShB,Remain1),
    shape_union(Remain0,Remain1,Sh1Remains).
convex_subtract(Sh1,[Sh2|Sh2s],Sh1Remains) :-
    (   convex_intersect(Sh1,Sh2,ShInt), ShInt == [] ->
        shape_subtract([Sh1],Sh2s,Sh1Remains)
    ;   shape_complement([Sh2], NotSh2),
        shape_intersect([Sh1], NotSh2, ShRemain0),
        shape_subtract(ShRemain0,Sh2s,Sh1Remains)    ).
```

Fig. 2. Operations on an n-dimensional space using CLP(Q) spatial_clpq.pl.

```
% Union = ShA ∪ ShB
shape_union(IdA, IdB, convex([X,Y])) :-  convex(IdA, X, Y).
shape_union(IdA, IdB, convex([X,Y])) :-  convex(IdB, X, Y).
% Intersection = ShA ∩ ShB
shape_intersect(IdA, IdB, convex([X,Y])) :- convex(IdA, X, Y), convex(IdB, X, Y).
% Complement = ¬ ShA
shape_complement(IdA, convex([X,Y])) :- not convex(IdA, X, Y).
% Subtract = ShA ∩ ¬ ShB
shape_subtract(IdA, IdB, convex([X,Y])) :- convex(IdA, X, Y), not convex(IdB, X, Y).
```

Fig. 3. Operations on a 2-dimensional space using s(CASP) spatial_scasp.pl.

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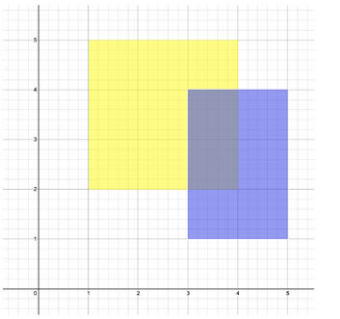
- `shape_subtract(ShA, ShB, Subtraction)`: Given two shapes ShA and ShB, the subtraction is a new shape $Subtraction$ that contains all points of ShA that are not in ShB, that is, $Subtraction = ShA \cap \neg\ ShB$ (lines 28-39). To compute the subtraction of a convex shape from ShA, we iteratively narrow its n-dimensional space, C_0, by selecting one convex shape from ShB, Sh_i, and computing the intersection of C_{i-1} and the complement of Sh_i, that is, $C_i = C_{i-1} \cap \neg Sh_i$. The execution finishes when all shapes have been selected or the i^{th} shape covers the remaining space C_{i-1}.

Example 7. These operations can be used with n-dimensional shapes. For simplicity, let us consider 2D rectangles: *r1* in yellow and *r2* in blue):

```
1 obj(r1, [convex([X,Y])]) :- X #>= 1, X #< 4, Y #>= 2, Y #< 5.
2 obj(r2, [convex([X,Y])]) :- X #>= 3, X #< 5, Y #>= 1, Y #< 4.
```

- The query `?- obj(r1,Sh1), obj(r2,Sh2), shape_intersect(Sh1, Sh2, Intersection)` returns: `Intersection = [convex([A,B])], A#>=3, A#<4, B#>=2, B#<4`
- The query `?- obj(r1,Sh1), obj(r2,Sh2), shape_subtract(Sh1, Sh2, Subtraction)` returns: `Subtraction = [convex([A,B]),convex([C,D])], A#>=1,A#<3,B#>=2,B#<5, C#>=3,C#<4,D#>=4,D#<5`



Example 8. In addition, they can be combined to verify IFC properties and/or (non-)geometrical information contained in the BIM model. The predicate `window_belongs(W,R)`, in Example 3, can be defined from the geometry of `W` and `R`, that is, `W` belongs to `R` if the intersection returns a non-empty shape.

4.3 Operations on n*-dimensional shapes under s(CASP)*

We will now sketch how the main operations on n-dimensional objects can be defined using s(CASP). We will take advantage of its ability to execute ASP programs featuring variables with dense, unbounded domains. As a proof of concept, Figure 3 shows the encoding of the operations for 2-dimensional shapes, with slight differences in the representation of the objects and shapes w.r.t. the representation used under Prolog:

- The predicates for union, intersection, complement, and subtraction receive the identifiers of the object(s), instead of the list of convex shapes.
- A convex shape in n dimensions is an atom with $n+1$ arguments. Its first argument is the object identifier and the rest of the arguments are the variables used to define the convex shape, for example, a 2D shape is an atom of the form `convex(Id,X,Y)`.
- The representation of the convex shapes is part of the program, for example, the rectangles $r1$ and $r2$ in Example 7 are defined with the clauses:

```
1 convex(r1, X, Y) :- X #>= 1, X #< 4, Y #>= 2, Y #< 5.
2 convex(r2, X, Y) :- X #>= 3, X #< 5, Y #>= 1, Y #< 4.
```

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This representation delegates the shape representation to be handled as part of the constraint store of the program. Therefore, a non-convex object is represented with several clauses, one for each convex shape, and a set of convex shapes is a set of answers obtained via backtracking.

Example 9 (Cont. Example 7). Let us consider the queries used in Example 7 under s(CASP) with the encoding in Figure 3.

- The query `?-shape_intersect(r1,r2,Intersection)` returns:

```
Intersection = convex([A | { A#>=3, A#<4 }, B | { B#>=2, B#<4 }])
```

- The query `?-shape_subtract(r1,r2,Subtraction)` returns two answers:

```
Subtraction = convex([A | { A#>=1, A#<3 }, B | { B#>=2, B#<5 }]) ? ;
Subtraction = convex([A | { A#>=3, A#<4 }, B | { B#>=4, B#<5 }])
```

5 Tracing (non)-monotonic changes in BIM models

Let us adapt the example presented by Arias *et al.* (2018) in Section 4.1, where different data sources may provide inconsistent data, and a stream reasoner, based on s(CASP), decides whether the data is valid or not depending on how reliable are the sources.

Here, instead of streams, we consider models. A shared model is updated by different experts, and updated models have to be merged to generate the next model in the chain.

Example 10. Consider a shared BIM model that contains information about room ventilation, a heating boiler feed system, and a fire safety regulation that states:

- If a gas boiler is used, the ventilation must be natural.[4]
- If an electric boiler is used, the ventilation could be either natural or mechanical.

Initially, the shared BIM model has no ventilation or boiler restrictions. Later on, the architect modifies the model by reducing the size of the window in such a way that ventilation cannot be considered natural any longer due to the new size. To comply with the fire safety regulation (and maintain the consistency of the model) the architect selects an electric heating boiler. Simultaneously, the engineer modifies the model by selecting a gas boiler because it is more efficient than an electric boiler. This would force ventilation to be natural.

Finally, when attempting to merge the updated models, an inconsistency is detected and the integration fails. A naive approach would broadcast the inconsistency to the architect and engineer, but we propose using a continuous integration reasoner to determine who is the expert whose opinion prevails and make a decision based on that. The other party needs then to be notified to confirm the adjustments.

Figure 4 sketches a continuous integration reasoner, adapted from the paper by Arias *et al.* (2018) and the encoding of Example 10 (Bim_CI.pl). Its goal is the detection of inconsistency in pieces of information provided by the different stakeholders. And then, depending on a given criterion (e.g. their responsibility/expertise), it would determine which data is valid (and eventually who should amend that inconsistency). Data labels are represented as `data(Priority, Data)`, where `Priority` tells us the degree of confidence in `Data`; `higher_confidence(PHi,PLo)` hides how priorities are

[4] The ventilation of a room is natural if the area of its windows is at least 10 percent of its floor's.

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```
1  %% BIM Continuous Integration
2  valid_data(P,Data) :-
3       data(P,Data),
4       not canceled(P, Data).
5
6  canceled(P, Data) :-
7       higher_confidence(P1, P),
8       data(P1, Data1),
9       inconsistent(Data, Data1).
10 higher_confidence(PHi, PLo) :-
11      PHi #> PLo.
12 %% Example
13 inconsistent(boiler(gas),
14                ventilation(artificial)).
15 inconsistent(ventilation(artificial),
16                boiler(gas)).
17 data(1,ventilation(X)).
18 data(2,ventilation(natural)).
19 data(2,boiler(gas)).
20 % data(3,ventilation(artificial)).
21 % data(3,boiler(electrical)).
22 % data(4,boiler(gas)).
```

Fig. 4. Code of the BIM continuous integration with an example.

encoded in the data (in this case, the higher the priority, the more level of confidence); and `inconsistent/2` determines, in lines 13–16, which data items are inconsistent (in this case, `ventilation(artificial)` and `boiler(gas)`). Lines 1–11, alone, define the reasoner rules: `valid_data/2` states that a data label is valid if it is *not canceled* by another data label with more confidence.[5] In this encoding the confidence relationship uses constraints, that instead of being checked afterward prune the search, but it is possible to define more complex rules, that is, to determine who is more expert/confident depending on the data itself (e.g. for discrepancies in the dimensions of a beam, the structural engineer is the expert).

Lines 17–19 define that initially, `ventilation(X)` holds for all `X`, but when the engineer selects `ventilation(natural)` and `boiler(gas)` this data has more confidence, so the query `?-valid_data(Pr,Data)` returns: `{Pr=1, Data=ventilation(A), A\=artificial}` because `boiler(gas)` is more reliable than `ventilation(X)`, `{Pr=2, Data=ventilation(natural)}`, and `{Pr=2, Data=boiler(gas)}`. If we consider that the architect selection has more confidence than the engineer's (by adding lines 20–21), the query `?-valid_data(Pr,Data)`, returns: `{Pr=1, Data=ventilation(A), A\=artificial}`, `{Pr=2, Data=ventilation(natural)}`, `{Pr=3, Data=ventilation(artificial)}`, and `{Pr=3, Data=boiler(electrical)}`. Note that now the answer `{Pr=2, Data=boiler(gas)}` is not valid. Finally, by adding `data(4,boiler(gas))` (line 22), we observe that answer `{Pr=3, Data=ventilation(artificial)}` is not valid. As we mentioned before, s(CASP) also provides justification trees for each answer (Bim_CI.txt) to support the inferred conclusions so the user can check and/or validate the correctness of the final results.

6 Evaluation

The reasoner and benchmarks used in this paper are available at https://gitlab.software.imdea.org/joaquin.arias/spatial, and/or at http://platon.etsii.urjc.es/~jarias/papers/spatial-iclp22. They were run on a macOS 11.6.4 laptop with an Intel Core i7 at 2,6 GHz. under Ciao Prolog version 1.19-480-gaa9242f238 (https://ciao-lang.org/) and/or under s(CASP) version 0.21.10.09 (https://gitlab.software.imdea.org/ciao-lang/scasp).

[5] Inconsistent data with the same confidence remain valid unless there is a more confident inconsistency.

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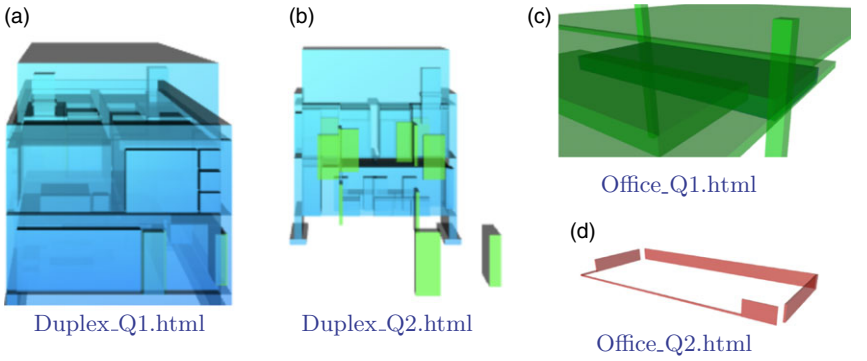

Fig. 5. Images in x3d corresponding to the Duplex and Office BIM models.

A direct performance comparison of our prototype with implementations in other tools may not be meaningful because they do not support the representation of vague concepts and/or continuous quantities. ASP4BIM by Li *et al.* (2020) overcomes most of the limitations of previous tools (see Section 7) but, since it is built on top of *clingo*, it inherits limitations already pointed out by Arias *et al.* (2022).

Firstly, let us use the program room.pl (Figure 1). As we mentioned in Section 3, it returns independent answers under s(CASP), that is, for the query `?- room_is(Room,Size)` we obtain a total of **14 partial models**: one for room $r1$, another for room $r2$, and two for each of other six rooms. On the other hand, the same program under clingo (room.clingo) generates **64 models**: all possible combinations such as `room_is(r1,big)` and `room_is(r2,small)` appear in all of them and for each room rX, 32 models contains `room_is(rX, big)`, while the other 32 models contains `room_is(rX, small)`. The exponential explosion in the number of models generated by clingo reduces the comprehensibility of the results (for 16 rooms it generates **16,384 models**, while s(CASP) generates only **30 models**). Moreover, the goal-directed evaluation of s(CASP) not only makes it possible to reason about specific rooms, but it also generates the corresponding justification, for example, room_r1.txt and room_r1.html for room $r1$.

Secondly, to validate the benefits of our proposal dealing with geometric information, we have implemented a spatial reasoner, in collaboration with VisuaLynk Oy, based on the spatial interface described in Figure 2. This spatial reasoner includes a graphic interface that translates the constraints back into geometry and generates 3D images with the results for the queries using x3d.[6] The benchmarks used are: (i) the ERDC: **Duplex** Apartment Model ERDC D-001 produced in Weimar, Germany for a design competition, and (ii) the Trapelo St. **Office** (IFC4 Edition), a 3-story office building where Revit HQ in Waltham is, which consists of three models (Architecture, MEP, and Structure).

For the evaluation, we translated the IFC files of the models to convert the geometrical data (and IFC labels) of the 286 objects of the Duplex and approximately 5000 objects of the Office Building (3639 objects in the architecture model and 1322 objects in the structure model) into Prolog facts. We defined a predicate `object/5`, where the first

[6] Reference textbook for learning Extensible 3D (X3D) Graphics available at https://bit.ly/3O1MqcH.

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argument is the IFC label, the second is the identifier, the third and fourth are the lower and higher points of the bounding box (resp.), and the fifth depends on the file (in the duplex file it is the centroid point of the box, in the architecture model of the office is "arq," and in the structure model of the office is "str"). Several queries, for both models, are available at duplex.pl and office.pl. Let us comment a few of them:

Example 11 (Duplex). Figure 5a shows the whole model of the Duplex (duplex.pl). The doors are in green and the rest of the objects are in blue (query $Q1$). Figure 5b shows the results of the query $Q2$ which imposes the constraints `Ya#<-4` to select certain doors, and `Y#>=-7, Y#<-4` to "create" a space (unbounded in the axis x and z) that defines a *slice* of the model. Constraints can be used in s(CASP) to reason about unbounded spaces, and finer constraints, such as `Ya#<-4.002`, can be used without performance impact. That is in general not the case with other ASP systems.

Example 12 (Office). Figure 5d shows the results of the query $Q2$ in office.pl, which selects objects of type *IfcBeam* in the Architecture model that are not covered by objects in the Structural BIM model. Figure 5c shows those objects that intersect the beam (query $Q1$). If that is the case, the uncovered parts are drawn in red. Note that these parts can be as thin as necessary, without negatively impacting performance.

The current development of the BIM reasoner is a proof of concept in which no optimization techniques have been applied. Nevertheless, the results from a performance point of view are also satisfactory. The query in Example 12 found the first beam with uncovered parts in **0.104 seconds** and evaluates the whole office, by selecting 691 beams from a total of 3639 objects in the architecture model and detecting the 511 beams not covered by the more than 1300 objects in the structure model, in **48 seconds**[7]

7 Related work

Many logic-based proposals have been developed to overcome the limitations of the IFC format and automated tools based on IFC, such as Solibri Model Checker (SMC) and the Corenet BIM e-Submission by Singapore Government (2016) to be adapted to different regulations. These limitations have been attacked using different approaches:

- Extended query languages to handle IFC data, such as BimSPARQL, by Zhang *et al.* (2018), that extends SPARQL with (i) a set of functions modeled using the Web Ontology Language (OWL), (ii) a set of transformation rules to map functions to IFC data, and (iii) a module for geometrical related functions. However, they require to pre-process the geometrical information contained in the model and/or have limitations to infer new knowledge, for example, the shortest path between two rooms.
- Minimal proof-of-concept tools, such as the safety checker by Zhang *et al.* (2013), the acoustic rule checker by Pauwels *et al.* (2011), and BIMRL by Solihin (2015), that show improved reasoning capabilities of w.r.t. commercial off-the-shelf BIM Sofware. However, all report limitations in the representation of geometrical

[7] Li *et al.* (2020) reports that ASP4BIM pre-processing of 5415 BIM objects takes 99 s.

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information and/or in the flexibility of the proposal to adapt the code and/or the evaluation engine for different scenarios.

- Translation of building regulation into computer-executable formats, such as KBimCode by Lee *et al.* (2016) which transcribes the Korean Building Act to evaluate building permit requirements. However, they report difficulties to translate vague concepts such as *accessible routes* (key information such as the function of a room is needed to derive the "accessible routes").

To overcome the limitations of these approaches, we propose using a goal-directed implementation of CASP, because Prolog and bottom-up implementations of CASP have limitations to modeling vague concepts and geometrical information simultaneously:

- **Prolog:** Since Prolog is based on the least fixed point semantics, the different answers generated by independent clauses correspond to a single model and are simultaneously true. Consider a program containing the facts `size_of(r1, small)` and `size_of(r1, big)`. If `size_of/2` is invoked in different parts of the program, it may assign two different sizes to the same room, which is against the intended interpretation of `size_of/2`. It is not possible to restrict `r1` to have only one of the two possible sizes everywhere in the program. Additional care (e.g. explicit parameters) is needed to force this consistency. Moreover, it is not easy to make use of default negation in Prolog, since its *negation as failure* rule has to be restricted to ground calls (e.g. the query in Example 1 is unsound under SLDNF) and it may not terminate in the presence of non-stratified negation (e.g. the query `?- small(r1)` in Example 2 does not terminate under SLDNF).
  While there exist implementations of Prolog, such as XSB with tabled negation, that compute logic programs according to the well-founded semantics (WFS), the truth value of atoms under WFS can be undefined, for example, the query `?- small(r1)` in Example 2 under WFS returns *undefined*.
- **CASP:** While a goal-directed implementation of ASP provides the relevant partial model, standard ASP systems that require a grounding phase in the presence of multiple even loops, for example, a unique vague concept referred to various objects, may generate a combinatorial explosion in the number of valid stable models, reducing the comprehensibility of the results.
  Moreover, these systems cannot (easily) handle an unbound and/or dense domain due to the grounding phase. Variable domains induced by constraints can be unbound and, therefore, infinite (e.g. `X#>0` with $\mathtt{X} \in \mathbb{N}$ or $\mathtt{X} \in \mathbb{Q}$). Even if they are bound, they can contain an infinite number of elements (e.g. `X#>0` $\wedge$ `X#<1` in $\mathbb{Q}$ or $\mathbb{R}$). These problems have been attacked using different techniques:
  - — Translation-based methods, such as EZCSP by Balduccini and Lierler (2017), convert both ASP and constraints into a theory that is executed in an SMT solver-like manner. However, the translation may result in a large propositional representation or weak propagation strength.
  - — Extensions of ASP systems with constraint propagators, such as clingcon by Banbara *et al.* (2017), and clingo[DL,LP], generate and propagate new constraints during the search. However, they are restricted to finite domain solvers and/or incrementally generate ground models, lifting the upper bounds for some parameters.

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Since the grounding phase causes a loss of communication from the elimination of variables, the execution methods for CASP systems are complex. Explicit hooks sometimes are needed in the language, for example, the `required` built-in of EZCSP, so that the ASP solver and the constraint solver can communicate. More details on standard CASP systems can be found in the paper by Lierler (2021).

Finally, let us analyze a recent proposal for safety analysis, ASP4BIM by Li *et al.* (2020), which is built on top of *clingo*, a state-of-the-art ASP solver. ASP4BIM overcomes most of the limitations of previous BIM logic-based approaches by (i) defining spatial aggregates in ASP, (ii) maintaining geometries in ASP through a specialized geometry database extended to support the real arithmetic resolution and specialized spatial optimizations, and (iii) formalizing 3D BIM safety compliance analysis within ASP. However, it inherits the limitations of ASP solvers, which require a grounding phase, when dealing with dense/unbounded domains (needed to represent time, dimensions, etc.) and/or understanding the answers due to the number, size, or readability of the resulting models. While the limitation of dealing with dense domains can be overcome by using discrete domains, for example, using integers to represent time-steps instead of continuous-time, it involves certain drawbacks: as pointed out by Arias *et al.* (2018) this shortcut may impact performance (by increasing execution run-time of *clingo* by orders of magnitude) and/or may make a program succeed with wrong answers (due to the rounding in ASP).

8 Conclusion and future work

We have highlighted the advantages of a well-founded approach to represent geometrical and non-geometrical information in BIM models, including specifications, codes, and/or guidelines. BIM models change during their design, construction, and/or facility time, by removing, adding, or changing objects and properties.

The use of CLP, and more specifically s(CASP), makes it possible to realize commonsense reasoning by combining geometrical and non-geometrical information thanks to its ability to perform non-monotonic reasoning and its support for constructive negation. Our proposal allows the representation of knowledge involving vague concepts and/or unknown information and the integration of (non-)geometrical information in queries and rules used to reason and define BIM models.

We have identified some future research directions.

- **BIM Verification vs BIM Refinement** The design and construction of a building is a sequence of decisions (setting dimensions, materials, deadlines, etc.) each of which reduces the degrees of freedom. A model refinement approach would generate a sequence of models based on the formal specifications of the regulations, client requirements, geometry, etc. Any change in the model chain should be consistent upwards, keeping the refinement structure.
- **Non-Monotonic Model Refinement** A monotonic evolution of a BIM model, following model refinement, ensures consistency. The natural flow of architectural development requires however the consideration of non-monotonic refinements due to unforeseen events, cost overruns, delays, etc.
- **Integrating logical reasoning in BIM Software** This proposal is an initial step that, together with other proposals such as ASP4BIM, may lead to a new

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paradigm in the refinement of BIM models that would improve the flexibility and reasoning capacity of the current standards. Its integration with commercial off-the-shelf BIM Software would require efficiency improvement, by adapting s(CASP) execution strategy or implementing specialized constraint solvers.

Conflicts of interest

The author(s) declare none.

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