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Why BIM cannot have more than four dimensions?

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Review

Dimensionality in BIM: Why BIM cannot have more than four dimensions?

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ABSTRACT

The paper examines proposals for *n*D BIM with respect to what may be considered a dimension and how dimensions relate to information in a symbolic representation. It establishes that 'dimension' is often used metaphorically to indicate information-processing capacities – an unfortunate usage in an area where the term is used literally. The paper proposes that a dimension in symbolic building representations should be a primary property of a symbol, not derivative, and moreover essential for the identity of the symbolized object, i.e. not subject to abstraction. On the basis of these principles, it is reasoned that BIM can only be 4D.

1. The significance of terminology

This paper is an investigation into what constitutes a dimension in BIM. It is not an idle exercise in terminological pedantry but an attempt at conceptual and operational clarity. It has long been established that the words and taxonomies we use to describe the world also shape our understanding of the things they denote. Paramount among these are analogical tropes like metaphors, metonymies and synecdoches. Love and life, for example, are seen as journeys. This produces a wide range of powerful and colourful expressions, like "taking a wrong turn" and "packing one's bags", but more importantly it reflects the way people conceptualize and approach love and life [1].

Such tropes also entail conceptual dangers. Social organizations, for instance, are often described as plants, so one can say that an empire grows, reaches maturity and then declines. This metaphor, however, may distort one's understanding of history: it has been likened to a meat grinder that reduces all facts into homogenized parts of a single story rather than treating them as distinct indicators of many different stories with complex interactions and various outcomes [2]. Words and taxonomies may therefore feed biases that restrict decisions and actions in ways that may not be apparent to their users [3].

In our case, one should question not only the incremental addition of dimensions to BIM but also the extended usage of the term 'dimension' in building representations: is it meaningful and correct? Does it improve our understanding of building information or, reversely, does it obscure fundamental information issues and lead to erroneous or wasteful approaches? In order to answer these questions, the paper proceeds with a non-exhaustive yet representative literature review that summarizes the discussion of dimensions in BIM. It then moves to a logical analysis of what constitutes a dimension in BIM, on the basis of recent theories in the philosophy of information. This returns three basic principles for the definition of dimensions, which are then used to test notions of *n*D BIM.

2. *n*D BIM

2.1. From 2D to nD

In the early days of BIM, much was made of its 3D capacities in order to suggest superiority over CAD. The latter was mistakenly presented as being merely 2D, just because it was predominantly used for the production of conventional 2D projections, like floor plans, sections and elevations. Interestingly, these projections also persist in BIM. Soon, however, BIM went beyond 3D and became *n*D: time was added as the fourth dimension and cost as the fifth [4–6], although resource information (for construction management) has also been proposed as the fifth dimension [7].

Beyond the fifth dimension, there appears to be lack of consensus [8]. Sustainability, project lifecycle, safety, energy, construction records (including quality, health and safety, and contract information), procurement, facility management, as-built and as-is information have all been called the sixth dimension of BIM [5,6,8–10]. Sustainability and facility management are the strong candidates for the seventh dimension [11,12], while some sources even include an eighth dimension, e.g. accident prevention [13].

The influx of dimensions is clearly indicative of the information capacities of integrated environments like BIM. Such environments entail the promise of including all complex hierarchies of domain

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information [11]. Each of these hierarchies appears to address specific aspects or tasks, so the expansion of BIM from 3D to *n*D is explicitly intended as support for the analysis of scheduling, costing, stability, maintainability, acoustic and thermal performance, health and safety, crime prevention etc. [4,14]. In other words, the building representation in BIM becomes directly connected to applications that utilize the information it contains.

The urgency to include and support aspects and tasks, and so utilize and justify BIM, is arguably the reason why the heterogeneity of proposed dimensions receives little attention. Even in the same publication, some dimensions are presented as analyses (5D as budget monitoring and cost analysis, and 6D as reviewing energetic efficiency), while others entail only the addition of data (7D as the collection of information on the operation and maintenance states of a building and its devices during their lifetime) [6].

Most publications on *n*D BIM focus on applications and their results rather than how relevant data are contained in the representation. It is often unclear what is added to the 3D version and how. In fact, 3D and 4D are often treated as the necessary information for any application. A publication on safety planning (which is often presented as a sixth or seventh dimension to BIM) affirms that all that is required is a 4D simulation of construction [15]. Another publication proposes 5D BIM through the addition of scheduling and costing but considers further analyses of quality, safety and carbon emissions as products of just 4D modelling [4]. Yet another publication suggests sustainability as the seventh dimension but presents sustainability as a *function* of social, economic, technological and ecological constraints throughout the lifetime of a building, and calculates it on the basis of 4D BIM and related external data [12]. Finally, two different publications describe 5D BIM in quite similar terms: as the use of 3D design information to produce outputs like quantity takeoffs and bills of materials [5,6].

In summary, BIM research appears primarily focused on what one can *do* with information in BIM rather than the nature and structure of this information. When people talk of BIM dimensions, they tend to use the term metaphorically, talking about dimensions to express information-processing capacities for various aspects. Such metaphorical usage of ‘dimension’ is quite common: we often speak of the social and the cultural dimension or the economic and the technical dimension etc. to indicate that there are several complementary aspects to a phenomenon.

2.2. Capacity and information

Literature confirms that the relation between capacity to cover a particular aspect and information actually contained in BIM is rather complex. For example, 5D is described as the capacity to generate cost budgets instantly but cost is not presented as a property of symbols in the model, like width or length. Instead, cost is linked to construction work packages like ‘brickwork on the first floor’ [10]. Such packages invariably involve decomposition of BIM symbols (e.g. of walls into different brick layers) and then clustering of decomposition products by kind and in relation to external parameters, such as productivity and scheduling. Other capacities refer to large chunks of the model or even the whole. Sustainability analyses, for example, build on the properties and relations of BIM symbols to appraise building performance, including comparisons between different design options [14]. Accident prevention amounts to exporting 3D BIM data to external analyses of hazard profiling for large building parts [13]. When new information is actually added, it is attached to the symbols of the 3D model: 7D BIM is proposed as integration of all building information relevant to facility management, including product and manufacturer data, maintenance and operation manuals [11].

The above suggest that higher BIM dimensions (higher than 4D) refer to information contained in the basic 3D or 4D model, only further processed to describe aspects of building behaviour or performance. The results and other, additional information are often connected to this basic model: even if it is not customary to include the manufacturer's name in a window symbol or attach the operation manual to it, there are no obstacles to incorporating such readily available information either as a property of the symbol or as a link between the symbol and external information sources.

3. Reasoning about dimensions in BIM

3.1. Symbolic representations

A recent comprehensive and systematic survey of *n*D BIM left information questions unaddressed. It merely observed that there is lack of consensus beyond 5D and recommended standardization of nomenclature to enforce consistency [8]. The present paper pursues a different goal: transparent, consistent definitions of what constitutes a dimension in BIM. Such definitions determine the structure of a building representation and how it accommodates various kinds of information. The consistency and accuracy of this information is a prerequisite to any of the applications promoted in *n*D research [5].

The term ‘dimension’ is used here in the literal sense of the mathematics of physical objects: as the minimum number of coordinates required to specify a point in space. This follows from the kind of objects described in a design: physical objects like building elements and spaces, described through their geometry, in the tradition established in the Renaissance [16]. The explicit inclusion of non-geometric information in BIM invites extension of dimensions to the whole information spectrum covered by BIM, beyond the three geometric dimensions. Just as the geometric dimensions, any other dimension should be present in individual symbols in a model, as information that describes a specific property of the denoted object.

The reason for this is that BIM is a *symbolic representation:* it uses discrete symbols to describe real-world objects, in particular building elements and spaces, in a way similar to how e.g. an alphabet uses graphemes (letters) to represent phonemes (sounds). The correspondence between symbols and real-world objects can be imperfect: the letter ‘a’ in English corresponds to five different phonemes, while in BIM each individual wall symbol is produced by a primarily geometric segmentation of the wall networks in a building [17].

Despite such limitations, symbolic representations have significant advantages, as evidenced not only in computerization but also in earlier technologies like movable type printing. Most advantages derive from the ability to produce a wide range of complex descriptions on the basis of a compact set of symbols. Information in these descriptions is accommodated in the symbols and their relations. A prime example of how properties and relations work is the way a quantity is represented using Hindu-Arabic numerals. In a decimal number, each numeral (drawn from a set of just ten symbols) indicates a quantity that should be multiplied by the power of ten indicated by the position of the numeral in the number (positional notation). The total quantity is the sum of all these multiplications:

$$1991 = 1 \times 10^3 + 9 \times 10^2 + 9 \times 10^1 + 1 \times 10^0$$

BIM also relies on a set of symbols, which are connected to each other in a graph that describes their relations. At first sight, the set of BIM symbols may seem too large, even infinite. To correct this impression, one should approach BIM symbols through their typological hierarchies. For example, one could argue that all internal walls can be described by the same symbol. Any refinement of this general type could then be seen as a matter of symbol properties: dimensions, materials, performance etc. may differ but the symbol remains the same, similarly to a letter ‘a’ that may come in different fonts, sizes or colours. In other words, typological abstraction can turn the symbols of BIM into a manageable set.

3.2. Symbols, properties and dimensions

Dimensions are present in BIM symbols, in principle as symbol properties (relations being primarily constraints on properties, e.g. the co-termination of two joined walls). A symbol in BIM has a number of properties, each representing a feature of the corresponding real-world object: geometric dimensions, materials, performance characteristics etc. Such properties populate both standards like IFC, which define symbols, and BIM software, where one enters and manipulates symbols. In both cases, BIM symbol properties tend to be a mixed bag: they include not only data like the length and height of a wall, which are essential for its description (*primary data*, according to semantic theories of information [18–20]) but also products of calculations (*derivative data*), such as the area and volume of the wall. This also applies to thermal, acoustic, fire safety and other performance characteristics, which can calculated on the basis of primary data like the dimensions and material composition of the wall.

It is important not to confuse known and unknown data with primary and derivative. Knowing the required performance of a wall does not make the performance characteristics of the wall primary data, only the starting point for solving the problem of which primary data would satisfice the requirements. This is what designers do as a design process progresses, adding missing primary data to the symbols and refining the existing ones.

The presence of both primary and derivative properties in a symbol conflicts with *normalization* principles in database theory [21–23]. These support reduction of redundancy through the elimination of dependencies: if both the birthdate and current age of a person are stored in a database, then the latter is redundant because it can be easily calculated on the basis of the birthdate. Redundancy increases not only storage space but also uncertainty because age-related queries can be answered through two distinct, potentially conflicting sources. Consequently, in a normalized database, only the birthdate (primary data) is stored, together with a function for calculating age (derivative data).

Unfortunately, BIM models are not normalized, which increases their size, causes problems with storage and reduces query efficiency [24]. Such problems have been widely acknowledged in literature from early on: it has been suggested that care should be taken that data are entered only once in a model, only by the most authoritative source, and that overlaps and duplicates should be eliminated, so that inconsistencies are reduced and the integrity of information sources is improved [25]. The issue with such apparently reasonable suggestions is that they do not address the problems at the fundamental level of the symbols. Drawing from the principles of information management rather than from the logic of semantic information or database normalization, they may help untangle a messy situation but ultimately fail to resolve the causes of the mess. In our investigation, the real solution requires looking at the structure of symbols and considering which properties may contain a dimension of the symbol.

Evidently, symbol properties containing derivative data cannot refer to true dimensions: area or volume properties do not qualify as dimensions, in contrast to length, width and height. This also applies to performance characteristics that are similarly calculated from primary properties. It furthermore extends to data that do not describe a property of a symbol but a relation to another symbol. In a paper on 5D BIM, construction resource information was proposed as the fifth dimension [7]. However, resources cannot be reduced to a property of the object to be constructed: a crane is not a property of a wall. Instead, in BIM both the crane and the wall are represented by distinct symbols. If the wall is to be constructed with the aid of the crane, then the two are linked in the frame of a particular work package and for a specific period within the construction schedule and site plan. Both symbols are explicit and separate; the one does not become a dimension of the other. This too agrees with database theory, which prescribes that different entities are described in different tables that are connected when necessary [22,23].

Focusing on primary data simplifies matters by eliminating a large number of derivative properties in a symbol but do all remaining properties qualify as dimensions? Is colour or texture a dimension? This question can be answered by considering what is essential for the identity of a symbol in BIM: what is necessary for defining something at even the highest levels of abstraction. Going back to a database example, the birthdate of a person is essential of their identity, so it cannot be abstracted without rendering the description of the person uncertain, e.g. "a John Smith born in the 1990s" versus "John Smith born on December 31, 1999".

Uncertainty should not be confused with fuzziness. Abstraction as applied in early design stages and representation for these stages involves fuzziness, e.g. concerning the precise dimensions and exact geometry of a wall [26]. There is, however, little uncertainty about the position and rough dimensions of the wall, including other walls it connects to and spaces it bounds. Other properties like the materials of the wall may be totally absent yet (deferred to later design stages) or implicitly defined through constraints like the load-bearing function or transparency of the wall.

One can therefore argue that also in BIM some properties must be present in a symbol, while others can be abstracted without loss of identity. Primary geometric properties are essential from the very beginning, given the geometric foundation of building representation. They may be fuzzy but must always remain within ranges of acceptable values, which are inherent to the type of the symbol. For example, the width of a wall may be defined as between 5 and 50 cm; the width of an exterior wall between 30 and 50 cm; and the width of an interior wall between 5 and 20 cm. Non-geometric properties, like the materials that comprise the wall, are subject to abstraction and deferment. In early design, a schematic wall may simply belong to the basic type 'party wall'. Its material composition is unknown, only constrained by performance requirements (e.g. structural function and thermal or acoustic insulation). This is different to the fuzziness of geometric dimensions because the material properties, even though primary, may be completely absent in the symbols.

With abstraction as an additional criterion, not all primary properties qualify as dimensions. Quite correctly within the framework of geometric building representation, no-one has argued that the materials of an object in BIM are dimensions. They are merely properties of a symbol and could be removed from it without destroying its identity. This also reflects our perception of real-world objects: we do not need to know all materials of a wall in order to perceive its presence and recognize it as a wall.

In summary, one can conclude this line of reasoning with three principles for defining dimensions:

1. BIM is a symbolic representation, so any dimension ascribed to BIM must be present in the dimensions of its symbols.
2. Not all properties of a symbol qualify as dimensions. Derivative properties, i.e. those calculated on the basis of other properties, are excluded.
3. Not all primary properties qualify as dimensions. Properties that can be abstracted without loss of identity to a symbol are also excluded.

The following section examines various notions of *n*D BIM on the basis of these principles, starting with 3D.

4. *n*D BIM revisited

4.1. 3D BIM

The question of whether 3D BIM truly has three dimensions is trivial. The geometric basis of the representation suffices as evidence. The geometry and position of any symbol (building element of space) can be fully and unambiguously described on the basis of three geometric dimensions.

4.2. 4D BIM

Time is the obvious and popular candidate for the fourth dimension. It is clearly primary information and acceptable as a dimension: it determines the history of a thing, including the incorporation of as-built and as-is information. Even in the simplest of models, a wall belongs to a specific phase or stage, e.g. the existing situation or the new construction, and so bears essential and fuzzy (rather than abstract) information on time.

Drawing from ecological psychology [27], one could compile the fourth dimension in BIM as a sequential list of *events*, including all milestones in the design, construction, maintenance and usage of the symbolized object, regarding either changes in its form and substance or in its relations to the environment. This makes the measurement of the fourth dimension primarily intrinsic (i.e. related to action and state rather than based on extrinsic units like hours and weeks) and variable (allowing for nesting of events into other events, making some subordinate and others superordinate relative again to actions) – in other words, structurally different to the other three dimensions.

Construction scheduling, the main current application of 4D BIM, uses events and their nesting to break down construction tasks into work packages [10]. These work packages refer to groups of symbols or parts of symbols, e.g. the external and internal brick layers of an external wall, the insulation, plaster and paint layers. This implies that the time dimension may often apply to specific components of a building element, which then have to be represented correspondingly separately, e.g. as subsymbols (so extending nesting to the symbols for building elements and components).

4.3. 5D BIM

The popular choice for the fifth dimension is cost. The initial problem with cost is that it covers a range of abstraction levels. Pricing, for example, may refer to the price of materials (e.g. sand), components (e.g. bricks) or whole assemblies (e.g. window). Unit prices for materials, components and assemblies delivered complete on site are clearly primary data. However, the cost of assembling these into a building element or a whole building is a complex function involving geometric, topological, economic and other factors. Cost expressed in terms of e.g. expenditure per square or cubic meter is therefore derivative information. This applies even to single components and integral assemblies: the cost of the same window at two different places in the same building may differ due to interfacing issues or equipment needs (e.g. scaffolding for placing at a height).

Consequently, cost is a function that relates to work packages rather than single symbols. Unit prices can (and should) be added as primary properties to symbols or subsymbols. However, despite being primary information, unit prices are not essential for the identity of objects: not knowing its prices does not render a symbol undefined. Therefore, cost cannot be considered a dimension in BIM.

4.4. 6D BIM and beyond

Even more than cost, aspects of building performance, such as sustainability, energy, safety and acoustics, do not qualify as dimensions in BIM. They all involve functions that apply to building parts or the whole and return results similarly general. Moreover, unlike unit prices, at the symbol level, they are represented by derivative data, such as thermal values, calculated on the basis of geometric and material properties.

Other candidates for dimensions, like procurement or facility management, may add primary properties to symbols, such as descriptions of state during an inspection. These properties can be very useful for various tasks, e.g. maintenance, but cannot be accepted as dimensions because they are not essential for the identity of the objects denoted by the symbols. The notable exception are time data, e.g. service dates, which nevertheless belong to the fourth dimension.

5. Discussion

Criticism in relation to BIM often focuses on issues perceived as barriers for the implementation and utilization of BIM. Most researchers appear interested in eliciting lessons from current BIM practices to improve deployment and implementation in the future. The cost of software and training, especially in relation to the means of small companies; the technical and legal complexity of the technology, in particular with shared central models; and the absence of standards and tools relevant to specific areas are frequently cited problems not caused but made evident by BIM [28–31]. More often problems are found to lie with users: their incapacity or unwillingness to adopt BIM [32]; lack of BIM knowledge, which reduces potential, including for collaboration [33]; lack of trust in each other's models; and genrally limited or superficial application of BIM [34].

It follows that, rather than express doubts anout the capacities and promise of BIM, researchers often call for a change of culture or organization in the construction industry to meet the constraints of BIM and so allow for correct implementation of the technology. Few tolerate hubrid BIM application as a valid practice but even then chiefly for studying the causes and effects of hybridization, so that users can move to full, integrated BIM [35]. Only a small number is critical of BIM itself: of its technocratic optimism [28] and its normative approach [36], which may underplay causal requirements for productivity improvement [37] or even lead to a digital divide, disenfranchising small firms [28].

Such criticism addresses the social and cultural aspects of BIM and suggests that reliance on BIM as an agent of change may be misplaced [28]. However, one should go beyond pragmatics and not take the structure and rhetoric of BIM for granted but scrutinize them more closely. For example, it is clear that there are still unsolved challenges in BIM when considered as a database and analyses of interoperability suggest that it may be usable syntactically but semantically it remains questionable [38]. Such scrutiny returns a better understanding of BIM, in both technical and theoretical terms. It also elucidates the character of its contribution to possible performance and productivity improvements in the construction industry, e.g. by pointing out that BIM may be more a tool of further specialization than integration [38]. The present paper does this for notions of dimensionality in BIM and suggests that their simplistic treatment may be connected to reported limited or superficial applications [34].

In a context where a term is used literally, usage of the same term metaphorically makes no sense. It is reminiscent of a spoof car advertisement in MAD Magazine, which bore the tagline “the Rolls-Royce of cars”. But even if the term is alien to the particular context, metaphors can mislead if their association with the literal meaning is invalid. Currently, people often use ‘DNA’ as a metaphor for the ingrained habits, preferences and practices in an organization such as a company or sports club. Such a genetic metaphor suggests inevitability or inescapability and therefore implies that change may be too hard or even unattainable. However, there are enough examples of change that radically alters a company's or club's ‘DNA’, e.g. when a director or trainer imposes a new vision and implements new practices. One should be careful with what a metaphor may imply.

In our case, ‘dimension’ is a term that should not be applied metaphorically or loosely in the context of BIM and building representations in the existing geometric tradition. It should be used in a sense that agrees with its literal, mathematical usage in the representation of physical objects, only extended to cover all information on these objects. Given the symbolic character of the representation, a dimension should apply not to BIM in an abstract, general sense (as an additional information-processing capacity) but be specifically and significantly present among the essential primary properties of each symbol.

On the basis of the above, it is argued that BIM can only be 4D. Any 'dimension' higher than that refers to capacities to calculate various aspects on the basis of symbol properties in 4D BIM. As explained previously in this paper, *n*D BIM literature largely acknowledges that 4D BIM already includes the data required for the calculation of other 'dimensions'.

The calculations necessary for these aspects are far from trivial. They require extensive domain knowledge, e.g. on the interfacing of building elements or the logistics of building sites, which explain the complexity of buildings and construction. They also involve demanding algorithms, e.g. based on computational fluid dynamics, which help designers and engineers understand the impact of their decisions.

BIM users should have a clear grasp of how a property value is returned, appreciate what it involves (especially in terms of necessary primary data users should include in a model) and in many cases also be able to control transparently how the values are produced. Reducing the underlying wealth of domain knowledge and computational processing to a simplistic notion of a 'dimension', implying a property that is easily, statically and deterministically added to a symbol or model, undermines the potential of BIM and limits the potential for performance improvement in building design and construction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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