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# Human-Centric Co-Design of Model-Based System Architecture

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## Abstract

Model-Based Systems Engineers, particularly those moving from software to systems engineering, claim that SysML-like notations, which are symbolic two-dimensional diagrams made of boxes and lines, are domain-independent, thus very convenient to support the cross-functional design of a system architecture. However, the abstract diagramming syntax of MBSE notations makes their adoption difficult, especially by notational nonexperts, and using iconic graphics is one way of improvement. Very few studies attempted to replace 2D diagrams with immersive 3D visuals without objective evidence. We assume that it is due to a lack of quality criteria to compare 2D diagrams with 3D visuals. This paper will argue that human-centric 3D visuals should replace MBSE diagrams where appropriate. A new human-centric MBSE modelling environment motivates the adoption of interactive and immersive 3D visuals to facilitate communication and participation in multidisciplinary co-design activities from mission to concept definition. Our claim is not supported by measured evidence, but a functional demonstrator provides observed evidence and, compared to existing studies, we discuss our proposal based on the Physics of Notation. Future studies will concentrate on the modelling of the behavioural and structural views and the definition of criteria to validate the human-centric MBSE modelling environment.

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*Keywords:* Model-based systems engineering; visual notation; graphical modelling; virtual reality; conceptual modelling; SysML.

## 1. Introduction

### 1.1. Context: Model-based system architecture design

Systems engineering (SE) focuses on architecture design from particular perspectives known as views: operational, functional, behavioural, logical, structural, etc. The architecture design process is supported by the Model-Based Systems Engineering (MBSE) approach, that is, the systematic and formalized application of modelling to support SE [1]. Models of a real object vary from very abstract symbolic models to very concrete iconic models [2]. The extensive use of symbolic, also known as conceptual [3] or pragmatic [4], models equips engineers with new abstract graphical notations that strive to facilitate communication. However, the introduction of MBSE notations gives birth to new challenges [5] – e.g. managing team understanding and commitment is hardly achievable with SysML-like notations [6] and the preliminary physical

embodiment (bounding box definition and spatial positioning of sub-systems) is impossible, with a block diagram.

### 1.2. Problem: Visual syntax of conceptual MBSE notations

Conceptual modelling languages for MBSE (e.g., SysML, Capella DSL or OPM), which rely on symbolic two-dimensional diagrams made of boxes and lines, are claimed – in particular by practitioners who moved from software to SE – to be domain-independent, thus very convenient to support cross-functional activities of system architecture. However, studies [2,7,8] point out a lack of acceptance of such interdisciplinary conceptual modelling languages because of the immense difference in abstraction with users' mental models. In addition to the engineers' reluctance to adopt diagrammatic notations, which meaning is purely conventional and must be learned, such vernacular languages fail to meet their fundamental purpose to integrate notational nonexperts

(e.g., business, marketing, operations, quality) whose voice is crucial during conceptual design. Indeed, the abstract symbols – nodes and edges – of SE languages can encode any fundamental SE concepts, but they do not ease a collaborative and integrated design. This hypothesis is corroborated by studies showing the benefits of mixing visual and participative Design Thinking techniques with SE [9].

One major reason influencing the quality of graphical modelling notations is visual syntax, but it is never discussed. Indeed, the semantic aspect of MBSE visual notations is receiving a lot of attention, whereas the choice of an appropriate form comes down to personal taste. This would not be a problem if existing notations – e.g. SysML – would have been built on a sound theory rather than derived from syntactically ill-defined visual modelling notations such as UML [10].

Several empirical studies show that iconic graphics should replace symbolic signs to reduce the cognitive load [11], accelerate recognition and recall [12], and make models more accessible to novices [11,13,14]. In a broader sense, people prefer real shapes to abstract objects [14,15]. 2D mechanical technical drawings with a high level of codification have been replaced by 3D iconic digital mock-ups supporting cross-functional design reviews. Similarly, one candidate solution to facilitate the integration – remotely or locally – of disciplines during the conceptual design of system architecture views is to equip system architects with a more natural visual syntax in a 3D stereoscopic virtual environment. Although according to the MBSE visions of NASA [16] and INCOSE [17] the future of SE is immersive, very few studies [18–22] attempted to integrate or replace 2D diagramming with immersive 3D visuals without objective empirical evidence. We assume that it is due to a lack of an agreed-upon set of quality criteria to specify, design and evaluate 3D visuals, whereas there are numerous criteria for 2D visual notations [3,23–26]. This motivates us to ask: **Why should human-centric immersive 3D visuals should parsimoniously replace 2D diagramming for modelling a system architecture design, especially for the early stage activities from mission to concept definition?**

### 1.3. Contribution

This paper will argue that 3D visuals should parsimoniously replace appropriate MBSE diagrams. A new human-centric MBSE modelling environment will encourage the adoption of interactive and immersive 3D visuals to facilitate communication and participation in multidisciplinary co-design activities from mission definition to concept development.

Our claim is not supported by measured evidence yet, but a functional demonstrator provides observed evidence without a formal measurement process and, compared to existing studies, we will discuss our proposal based on comparison criteria which serve as evidence backed by other references.

## 2. Literature review

The literature review starts with a brief review of MBSE practices. Second, is a sum-up of quality criteria for designing and evaluating visual notations. The third part gives the gist of studies that use immersive 3D graphics to support MBSE.

### 2.1. System architecture design frameworks

A widely recognized multi-view definition of a system is the function-behaviour-structure (FBS) ontology [5] where the designer’s task is to define the functions – “what it is for” –, the behaviour – “what it does” –, and the structure – “what it is”.

Recently, SysML was proposed to capture, analyze, evaluate and communicate system information. Compared to UML, SysML was intended to support the modelling of a broader range of systems including hardware, software, data, personnel, procedures, and facilities. SysML is a headless body since it offers a set of diagrams to capture information without a method. Thus, SysML practitioners worked out numerous methods (e.g. OOSEM, Magic Grid, ISE&PPOOA, SYSMOD, Harmony-SE, MOFL, SysCARS, ASAP, SE-READ). However, studies report numerous limits of SysML-based design, such as inadequate software features [4], complex and laborious modelling operations [27], too much modelling freedom [27,28], information overwhelming [28], complexity (variety and quantity) with large SysML models [6,29], extra time to learn a domain-specific language [30], poor management of multiple views on a technical object [28], and too many diagrams and interdependencies [29].

Despite the efforts to equip systems engineers with standardized graphical modelling notations, the influence of software engineering without crucial changes for embracing systems thinking leads to poor SE visual notations that inherit syntactically ill-defined notations such as UML [10].

### 2.2. Quality of graphical conceptual modelling notations

Most efforts to define new 2D graphical conceptual modelling notations are spent on designing semantics while ignoring or undervaluing the role of visual syntax [23]. The poor quality of graphical conceptual modelling notations harms acceptance from the non-specialist audience [8,10,23]. Consequently, “*practitioners spend inordinate effort transposing models from rigorous tools to non-structured formats to overcome the acceptance problem. In the process, the connection to the source repository is lost, thereby destroying integrity, reusability, maintainability and currency of the derived output when the source changes*” [10]. As alternative solutions, one can enrich block diagrams with iconic graphics [11,31], engineering sketches [2,8] or simply embed them in hand-crafted PowerPoint slide decks [32].

The lack of theoretical rigour when designing visual dialects leads to undesired properties – e.g., a graphical modelling notation should satisfy the principle of semiotic clarity that prescribes a 1:1 correspondence between semantic constructs and graphical symbols. However, it was shown that UML contains numerous instances of symbol redundancy [23]. By inheritance, symbol redundancy or overload is also affecting SysML. For instance, companies involved in the SysML working group of the INCOSE French Chapter use three different SysML graphical symbols (activity, bloc, bloc property) to perceptually represent the fundamental SE concept of function. Semiotic clarity is not the only principle for evaluating and comparing visual notations. Another example is the very poor discriminability of conceptual modelling

notations that consist of shapes – mostly rectangle variants [14] and connecting lines – that are visually too similar [23]; therefore leading to confusion [33]. The comparison of the UML, IE, and Oracle conventions showed that, without a sound theory, visual notations can get worse rather than better over time [23]. SysML-like diagramming notations that support an MBSE approach repeat the same mistakes. Among the numerous quality criteria for 2D visual conceptual modelling notations, the Physics of Notation [23] plays a crucial role.

To replace symbols with a meaning that is purely conventional and must be learned, it is possible to use 3D visuals – e.g., rich images – with a high degree of semantic transparency so that a novice reader can infer or easily learn the meaning from the appearance [14,23]. The natural mapping between the set of concepts and the set of symbols relies on physical analogies, visual metaphors, and cultural associations to design physical objects [34]. This is what is often referred to as the “naturalness” or “affordance” of a virtual environment.

### 2.3. VR for Architecture, focus on the operational view

Virtual reality (VR) offers the opportunity to encode domain knowledge in rich representations that require less decoding efforts for notational nonexperts in conceptual modelling.

Although 2D technical drawings require learning a new language to decode symbols, VR eases the manipulation and understanding of 3D geometries [35]. However, this result stands for concrete objects but does not directly apply to abstract ones (e.g., mission, function, requirement, etc.). There are two alternatives to overcome this issue. First, one can invent iconic representations to replace symbolic ones (e.g. text or bloc diagrams) so as to perceptually represent abstract objects with a lower degree of abstraction. For instance, islands [36], cities and solar systems [37] metaphors were developed to represent very abstract software concepts (e.g. packages, lines of code, classes, interfaces) usually captured in UML diagrams. A literature search indicates that the only MBSE application focuses on graphical mission scenarios in the defense industry [20]. Nevertheless, existing proposals fail to provide empirical evidence that 3D iconic metaphors add value. The second alternative is to merely implement symbolic representations in an immersive 3D virtual environment. This was tested with BPMN [37–40] and UML diagrams [41] but not with MBSE notations except for VR-based model-design reviews [21].

### 2.4. Summary of the literature review

The literature review points out that MBSE relies on poor software-oriented diagramming leading to adoption challenges, especially by notational nonexperts, which hampers their active participation in multidisciplinary co-design activities. Few recent research studies conducted by the software community propose to use immersive 3D visuals to ease communication with UML and BPMN diagrams, which is a motivation-increasing alternative to the very abstract symbolic 2D diagramming visual notations. However, the engineering design community misses VR-based functional demonstrators applied to MBSE and metrics to perceive the value of

interactive 3D graphics, especially for the co-design of architecture and not only the visualization of existing models.

## 3. Research method

We argue that human-centric and immersive 3D visuals should parsimoniously replace appropriate MBSE diagramming to facilitate communication and participation in multidisciplinary co-design activities from mission definition to concept development. To support this claim, based on the literature review, we will follow a research method that starts with the definition of a minimum and consensual ontology of SE concepts to be encoded with both solutions. Then, we will go through the selection of a test case to compare two competing solutions. A functional prototype of our human-centric MBSE modelling solution will be detailed. Finally, 3D visuals will be compared to SysML diagrams. Because of the limited number of pages, we limit the comparison to the definition of the system lifecycle and context.

## 4. Diagramming VS. Immersive interactive 3D visuals

### 4.1. Ontology of an operational view

A review of the MBSE methods (Sec. 2.1) shows that there is no consensual ontology, but there exists a set of common concepts defined and communicated from mission definition to concept development. For the first version of our prototype, the list of concepts, which is not fixed or immutable, includes:

- *lifecycle* including *phases* and *transitions* between phases,
- *external entities* that belong to the environment and have an indirect influence or direct interaction on the system,
- *interfaces* between the external entities and the system,
- *services* that the system provides to stakeholders and *constraints* that external entities impose on the system,
- *operational scenarios* that describe the temporal sequence of functional interactions between the system and the external entities to achieve a mission.

### 4.2. Test case

To discuss the SysML diagrams compared to the immersive 3D visuals, the Go-To telescope is preferred as a test case [42] to which the reader has to refer to find the SysML diagrams.

### 4.3. A human-centric immersive MBSE modeling environment

Based on the ontology of the operational view, we propose a human-centric modelling environment to co-design system architecture with interactive and immersive 3D visuals. The VR software Unity is preferred and the application is deployed on an HTC Vive Cosmos Head Mounted Device that is controlled by the system architect whereas other participants indirectly contribute to the architecture design in real-time via a powerwall that streams the system architect’s field of view.

For encoding the concepts of a lifecycle, we designed an exocentric metaphor, that is, a God’s eye viewpoint, where users interact with the virtual environment from the outside via the well-known World-In-Miniature technique [43]. Each

phase of the lifecycle is an empty World-In-Miniature (Fig. 1) that the user instantiates from a library by a drag and drop anywhere in the 3D space. The encoding of a transition between two phases is a 3D arrow connecting two World-In-Miniature metaphors. Note that the designer can rearrange phases and transitions to model a closed or open lifecycle.

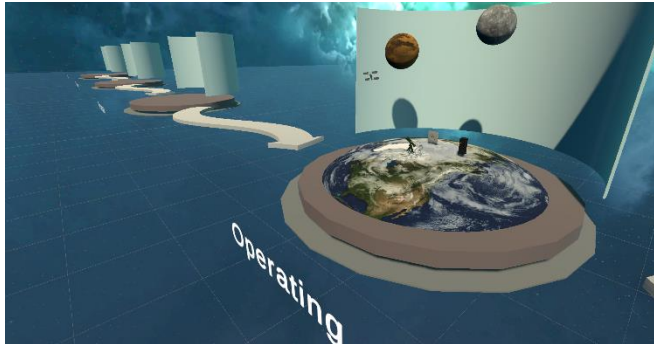


Fig. 1. System lifecycle modelling with immersive 3D visuals

For encoding the context of a given phase of the lifecycle, we designed an egocentric metaphor where the user is interacting from inside the environment, that is, the virtual environment embeds the user. Thus, when the user teleports himself inside a World-In-Miniature, he gets immersed at life-size. Note that it is possible to concurrently model the context of multiple phases thanks to a multiplayer capability. Another collaboration option consists in streaming the 3D visuals seen by the system architect in the HMD to a powerwall that is visible by other participants involved in the integrated design.

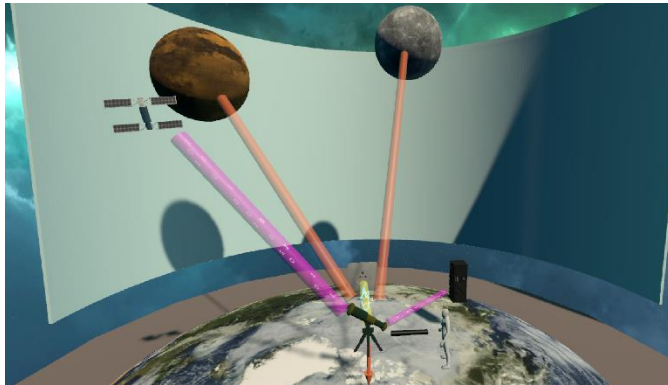


Fig. 2. Context modelled with immersive 3D visuals

To create the external entities belonging to the environment and influencing or interacting with the system, the system architect has access to a library of 3D objects that he can freely instantiate by drag and drop in the 3D space. Although the solution intends to support conceptual modelling, we have decided to encode concrete and abstract objects with iconic representations when possible. For instance, the telescope and the external entities (Fig. 2) are perceptually represented by iconic 3D visuals which facilitates the inference of the meaning of the representation from its appearance. However, some abstract objects are encoded with symbolic signs. For instance, ray casting symbolizes the external interfaces with a texture for each type of flow (material, information, and energy) and the direction of flows is captured by the color of ports.

Instead of opening two SysML diagrams in a 2D screen-based modelling environment, the architect naturally navigates from the lifecycle to the context of each phase in an unlimited

3D continuum. This capability is even more powerful when considering all MBSE views and the corresponding models that can be unified in a holistic virtual environment. *One may argue that all information could be captured in a single SysML diagram avoiding the need to navigate, but this is not possible since considering all lifecycle phases would increase the number of external entities and interfaces making the model too difficult. Moreover, the static illustration Fig. 1 and Fig. 2 does not show the description of functions and operational scenarios which are dynamic and that are captured in other diagrams such as use case, activity and sequence diagrams.*

#### 4.4. Comparison

The comparison of SysML diagrams with immersive 3D visuals relies upon the principles of the Physics of Notation [23], except cognitive fit which does not directly apply in 3D.

**Semiotic clarity** is the satisfaction or not of a notation system in Goodman's theory of symbols – i.e., no symbol redundancy, overload, excess, and deficit. It was demonstrated that UML includes several instances of symbol excess [23]. SysML being a UML profile, it also violates one of the basic quality criteria for visual notations. For instance, the fundamental concept of function encoded by an activity, a block or a block property. In our virtual environment, we make sure that one concept is systematically perceptually encoded by a unique symbolic or iconic 3D representation.

**Perceptual discriminability** is the ease and accuracy with which symbols can be differentiated from each other. Conceptual modelling notations such as SysML use a perceptually limited repertoire of shapes [14], mostly rectangle variants, and connecting lines that are visually too similar to distinguish different concepts. When using iconic 3D visuals, the visual distance between the visuals is relatively large. One may argue that this makes the modelling activity more laborious as it requires a 3D visual for encoding each concept, but with the large adoption of 3D media and 3D printing techniques, there exist numerous online databases of 3D iconic representations (e.g., sketchfab, turbosquid, free3D).

**Semantic transparency** is the extent to which the meaning of a symbol can be inferred from its appearance. When possible, the use of iconic representations such as rich pictures or 3D graphics to replace symbolic 2D representations provides rare but highly visually appealing representations with an effective use of semantic transparency [23] and reduces the cognitive load [11]. The preference for iconic representations rather than symbolic ones is even more important when the activity includes notational experts and novices like in systems architecture design. Indeed, iconic graphics speed up recognition and recall [12] and improve intelligibility of diagrams to novices [11,13,14]. Although the appearance of 2D blocs can be enriched with 2D images – which hide the type of a block –, the appearance of iconic 3D signs (Fig. 4) is more evocative. People prefer real shapes to abstract objects [14,15].

**Complexity management** is the ability to represent information without overloading the human mind. The substitution of appropriate 2D symbols with iconic 3D visuals lessens the diagrammatic complexity, whereas the use of iconic representations reduces intrinsic and extraneous cognitive

loads [11]. Electroencephalogram-based experiments also showed that stereoscopic 3D virtual environments require a significantly lower cognitive load than 2D projections [44].

**Cognitive integration** is the additional cognitive demands on the reader to mentally integrate information from multiple diagrams used to represent a system. Reading SysML models requires establishing interdependence between relevant system elements dispersed across multiple diagrams because of a limited modelling space. Using a unique VR environment without spatial constraints automatically reduces diagrammatic reasoning. Indeed, users experience a virtual world without boundaries and can navigate into a continuum of information. This reduces the perceptual integration effort to establish interdependence between relevant system elements that have been originally dispersed across multiple models and the conceptual integration effort to generate and refine hypotheses by combining information inferred from the models.

**Visual expressiveness** is a measure of the utilization of the graphic design space based on the number of visual variables used in a notation. SE notations use a limited range of visual variables, mostly rectangles variants, which are the least effective shapes for human visual processing, whereas curved 3D and iconic shapes should be preferred [12,15]. Therefore, the use of 3D iconic visuals in our environment is more suitable than 2D diagramming in terms of visual expressiveness.

**Dual coding** is the use of textual encoding to supplement rather than to substitute for graphics since, according to dual coding theory, using text and graphics together to convey information is more effective than using either on their own. Both solutions support dual coding, but since most 3D visuals are iconic with a high level of semantic transparency, they do not need dual coding, which makes it graphically more economic. When 3D symbols are inevitable, like for lifecycle phases or flows (Fig. 1), dual coding is used.

**Graphic economy** limits the number of graphical symbols in a notation to consciously maintain meanings of symbols in working memory. In the 3D environment, graphic economy is improved by the extensive use of iconic 3D representations. Few concepts such as lifecycle phases and transitions as well as flows and ports of interfaces remain encoded by 3D symbols.

#### 4.5. Discussion

Although quantitative evidence is necessary, the qualitative comparison encourages us to claim that human-centric immersive 3D visuals should, where possible, replace MBSE 2D diagrams to facilitate communication and participation in multidisciplinary systems architecture co-design activities.

Why 3D visuals should not replace all MBSE diagrams? First, there are diagrams that capture tangible concepts (e.g., human and physical entities) for which there is a natural mapping to concrete 3D visuals. Second, there are diagrams that represent abstract concepts (e.g., lifecycle phases and logical interfaces) which are invisible but for which 3D visuals increase the figurative tangibility, that is, the ability of an actor to mentally grasp (i.e., understand) an abstract concept that was defined by someone else. Finally, there are diagrams containing very abstract concepts (e.g., requirements and functions) for which 3D visuals are simply not suitable and should be captured by exploring the existing 3D scene with

other modalities. The flexibility of our modelling environment allows this change of modality according to the MBSE activity to be performed. For instance, the definition of requirements is achieved with a 2D screen and a mouse to select objects in the 3D scene and a keyboard to write requirements. Functions, which are transformations of inputs into outputs, are captured as voice recordings after defining interfaces. Mixing concrete and symbolic 3D representations with text and voice recordings enables architects to not only capture traditional SE concepts like an MBSE software, but also to define shapes and spatial positions. Finally, VR offers a Human-Computer Interface to naturally define the position and orientation of objects in a 3D space without physical boundaries.

## 5. Conclusion

In this paper, we asked: why should human-centric immersive 3D visuals should parsimoniously replace 2D diagramming for modelling a system architecture design, especially for the early stage activities from mission to concept definition? Based on the latest improvements in VR, we argued that immersive 3D visuals should replace appropriate MBSE symbolic diagrams. The introduction of a new human-centric MBSE modelling environment motivated the adoption of interactive 3D graphics to facilitate communication and participation in multidisciplinary co-design activities from mission definition to concept development. By using the use case of a Go-To telescope, we qualitatively compared the SysML diagrams with our 3D visuals based on the quality principles defined in the Physics of Notation. The discussion argues that 3D iconic visuals outperform the appropriate 2D symbolic diagrams on all quality principles, especially due to its semantic transparency and visual expressiveness to satisfy notational nonexperts involved in the conceptual design process as well as its cognitive integration that provides systems thinkers with a holistic view.

As future works, we plan to integrate the behavioural and structural views [45] into the immersive modelling environment and empirically demonstrate its added-value.

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