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Saoussen Dimassi, Frédéric Demoly, Christophe Cruz, Samuel Gomes. From Dispersed Knowledge to Ontology: A Proposal for Formalizing and Integrating 4D Printing in Design. 18th IFIP International Conference on Product Lifecycle Management (PLM), Jul 2021, Curitiba, Brazil. pp.80-95, 10.1007/978-3-030-94399-8_7. hal-04195244

HAL Id: hal-04195244

<https://inria.hal.science/hal-04195244v1>

Submitted on 4 Sep 2023

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From dispersed knowledge to Ontology: A proposal for formalizing and integrating 4D printing in design

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Abstract. Current research efforts related to 4D printing (4DP) has reached an unprecedented level in smart materials (SM) driven era. It is mainly about manufacturing parts/products combining additive manufacturing (AM) techniques and reactive matters. The latter association leads to transformable products presenting abilities of shape morphing, colour changing, etc., after being triggered with adequate stimuli. Thus, many ad-hoc solutions appeared in literature, in the last decade, with different dispersed expertises. Indeed, the information available about how to carry such smart products automatically is limited and poorly known. This lack of common core knowledge is primarily due to the various skills involved in printing stimuli-reactive products. Hence, different user profiles, i.e. the product designer, product architect, process planner, etc., cannot take profit from this pioneering technology. Thus, the product design process must incorporate such technology to tackle design for 4DP issues. In this context, this paper proposes a framework that starts from establishing an ontological structure for the semantic and logical description of smart products respecting multi-dimensionalism (three- and four-dimensional objects), semantic reasoning theories and description logic language. The latter describes formally the proposed ontology and defines knowledge extraction from the above-mentioned ontology respecting some user profiles needs. At the end, a strategy for integrating this federated knowledge in cognitive CAD methods and tools is deployed.

Keywords: Ontology, Semantics, Smart Products, Knowledge, Product Design Process, Design for 4D Printing.

1 Introduction

4D printing (4DP) is gaining increasing interest due to the smart materials (SM) capabilities and additive manufacturing (AM) techniques. This technology associates both competencies to deliver smart part/product that is sensitive to specific stimuli, so, transformation capabilities are incorporated into the manufactured products. Despite still being in its infancy phase, 4DP generates considerable interest due to its crucial role in manufacturing transformable and adaptive structures conducting an estimable change [1]. Combining AM techniques with SM provides a temporal dimension (t) to the three geometrical dimensions (x,y,z). Last decade was considered to be the triggering period

of this innovative technology. Preliminary studies about 4D printable structures involve multi-material printing possibilities [2] to correlate inert to smart materials. Hence, the products are designed and manufactured as living components capable of moving to various physical states or geometric arrangements concerning their trigger conditions [3]. Triggers, i.e. stimuli, are needed to activate shifts at multiple levels, e.g. structure, form, property and functionality. For all the stakeholders mentioned above, 4DP is considered a promising industrial technology for the next generation of live products [4]. So that, the next decade is about to witness a significant ascent in designing and manufacturing transformable and reactive products. But most of the previous works have only focused on multiplying the used materials, stimuli, AM processes and the possible transformations with neglecting the need to theorise the knowledge behind. For that reason, the dispersed knowledge must be formalised in rigorous understanding; therefore, product designers, architects, material experts and process planners can significantly restate it in part/product design phases. Many researchers were interested in the concept of design for excellence DFX [5], which attempts to concurrently scrutinise product lifecycle using assembly, processing, recycling, and mainly other product features.

Similarly, design for 4DP problems needs to be tackled, i.e., developing knowledge models, methods, and tools to optimise a design for 4D printable product. Actual 4DP experiments and related proofs-of-concept are introducing disparate knowledge with interdisciplinary expertise. Consequently, the research goal is set to emphasise and federate 4D printing-related conceptual knowledge involving AM processes and techniques, SMs, stimuli and transformation problems. Hence, an ontology is implemented for this purpose thus the knowledge-behind is computer-readable and reusable at different design stages of the product. In other words, user profiles are supported to make the best choices, in the future, during the design phase of living and transformable objects. Nevertheless, the user profiles are the product architect (the project leader: he plans the transformation and the ultimate changing behaviour), the product designer (he predefines and redefines the geometry and the material distribution accordingly in conceptual design and preliminary design phases), the material expert approves the choice of product materials and the process planner is responsible for AM process choice and AM operations planification. So, an ontology is proposed to ensure the conceptual representation and logical description of transformable objects in the age of 4D printing. Besides, this ontology is formalised and presented in description logic (DL) language in order to demonstrate the possible knowledge extraction for each user and to facilitate future tasks of knowledge extraction within each user profile needs. This paper is organised as follows: the second section set up some relevant research literature. The third section proposes a framework for developing the proposed ontology and presenting the possible usage scenarios after implementing a domain ontology that serves as a "knowledge-base" for 4DP technology. Moreover, it presents the formalisation of the ontology using DL language and the definition of the knowledge related to product designer (design view) and product architect (transformation view). The fourth section illustrates a case study for demonstration: a deployable satellite

realising an unfolding transformation. Finally, conclusions are stated, and future work is addressed in the last section.

2 Background

Transformability and product changeability during or post manufacturing were already addressed in the last two decades, before the term 4DP has been coined. Previously, this research area was discussed by polymer scientists with consideration to form morphing structures and shape memory polymers (e.g. artificial muscles) [6-7]. Preliminary studies of polymers have considered behavioural studies, glass transition temperature, stress magnitude and elasto-viscoplasticity deformation [8-10], with widespread usages through various domains [11-15]. Along with the cited works, particular substance embedding dynamic behaviours have been developed to accomplish primitive transformations such as bending, twisting and folding – until exposed to solvent, light, magnetic and electrical fields [16-17]. Besides, shape-memory composites and pH-responsive materials like hydrogels were developed for self-folding transformation, presented in many experiments using origami hinges or multi-layered materials [18-20]. Accordingly, the above research progress has initiated programming materials by tuning constitutive laws [21]. As a result, 4DP was coined to cover these attempts of AM technologies, particularly material jetting [22-23]. Much of their proposed study deal with ad-hoc works involving multi-materials, immediately from the printing bed, dipped in water (e.g., hydrophilic silicone material) or triggered by electricity. A growing body of literature has examined folding applications so that researchers have shown several shifting structures based on different stimuli, structures and material distributions [24]. Thus, 4DP allows transformation-based sequence over spatial dimensions (i.e., 2D and 3D) from one state to another in terms of structure, properties and functions [25-26]. Furthermore, [27] illustrated a linear stretching structure (from 1D to 1D), a 2D folding and stretching structure, and a 3D topographical surface transition. Then multiple transformation-dimensional possibilities were demonstrated, and numerous study niches were opened. Other researchers have based their efforts on manipulating bending and folding primitives by using reverse engineering and measuring such parameters such as fibre weight, hinge length and position, strain, temperature, deformation and activation processes [28-30]. [31] reviewed bending structures' kinematic analyses and their corresponding folding patterns triggered by multiple factors (e.g. thermal, chemical, etc.). Similarly, diverse plastic materials have been developed to fuel advancement in 4DP, such as gels with photo-responsive fabrics, thin composites and polystyrene [32]. Henceforward, it can be estimated that the fundamental objects constructing 4DP technology are triggers, geometry, AM processes and techniques, SMs and transformation functions [2]. Merely all the experiments have used proof-of-concept machines/devices, and many AM methods, ranging from material extrusion (fused filament production and direct ink writing), photopolymerisation (stereolithography, digital lighting processing) to material jetting (drop-on-demand) [33-34]. Here on, advances are becoming more mature, like the research works of [35-36] in which, they determine SM distributions at the early design stage of 4D printed structures by

considering a voxel-based simulation approach coupled with genetic algorithms. The above works provide plenty of interrelated information and unstructured knowledge. Then, it shows the complexity of integrating 4DP in a complete product life cycle, i.e. design, simulation, production, etc. Besides, designers and architects still can't take profits from this innovative paradigm. So, capturing the knowledge behind is crucial at this stage.

Ontology is defined as a "knowledge-base" – which current topics, objects, processes and theories as entities or concepts and relationships as unary or binary predicates – designed with axioms, definitions and theorems [37-39]. As a tool for capturing knowledge and formalising it, ontology was introduced recently in mechanical engineering. Hence, a feature-based ontology was developed to gather semantic knowledge in order to integrate computer-aided design (CAD) and computer-aided process planning [40]. The interoperable protocol was to communicate existing and following generation CAD programs. [41] have proposed an ontology to support the preparation of the first-order process for sheet lamination technology. For the same manufacturing process, [42] developed the ontology embedding manufacturing rules for automated feature identification technique. An ontology dedicated to designing AM was suggested in order to produce a system for component design details, AM processes and the ability to represent design rules [43]. It is then possible to test design features against production restrictions. Similarly, an informal model of generative ontology was developed for AM method planning [44]. An ontological system for selecting and semantically extracting materials in domain-oriented information from a material viewpoint was provided by [45]. [46] showed the use of basic formal ontology (BFO) over-engineering realms in the interoperation, inquiry, and parallel acquisition of information. Moreover, an ontology has been built to formalize 4DP knowledge at a product/part level by basic formal ontology BFO [47]

On the other hand, description logics are formal representation languages that have been initiated with Karlsruhe and are decidable fragments of first-order logic [48]. It is of particular importance in providing logical formalism for quality ontologies. In DL, a distinction is drawn between the so-called T-Box (terminological level) and the A-Box (assertional level). A DL terminology is a set of terminological axioms, consisting of terminological constructions of ontological elements. Ontological elements are of two types: non-relational and relational elements. Non-relational elements are concepts (classes) and datatypes, and relational elements are roles and attributes. Hence, ontologies and DL language are essential for implementing a preliminary design phase for 4DP and describing the spatiotemporal phenomena behind these transformable structures.

The wide spectrum of research initiatives in mechanical design world [49-51] and the current limitations of 4D printing demonstrate that tackling a proactive design process for this technology is a research area in a full expansion. Indeed, interdisciplinary issues in product design and development have been addressed in the past especially in the product development phase where design activities and decisions have a great impact on downstream processes (i.e. manufacturing, assembly, maintenance, etc) [52-53]. Nonetheless, the recent implementations of design for X - in which X could be for example assembly or manufacturing - have led to enormous benefits including

simplification of products and reduction of costs [54-56]. The latter is encouraging to propose a design for 4D printing roadmap that can start eventually with a design for 4DP framework that promotes a multiple involved stakeholders (i.e., product architect, product design, material expert, etc.) and various 4DP components (i.e., materials, stimuli, processes, transformations, etc.).

Consequently, and regarding the aforementioned research works, it seems crucial to propose an ontology federating the 4DP knowledge and to formalise it, using DL language in order to apply a top-down design strategy and to propose knowledge-based design for 4DP approach.

3 The ontology framework

The ontology framework presented below in Fig.1 tries to establish a comprehensive method of formalising and describing the knowledge qualitatively behind 4DP. The 4DP ontology is implemented with refer to multiple proof-of-concepts (ad-hoc research experiments) and data sources, i.e., AM processes and techniques standards, materials databases. Nevertheless, it is crucial to address and acquire fundamental theories like multi-dimensionalism since the research gap is handling transformable objects over time, semantic reasoning to cover the articulation between immaterial and material objects, mereotopology to address spatial relationships (parts and wholes relationships) and changeability management so that the ontology is continually updated.

Once the classes, data- properties and instances are set, the ontology is modelled within distributed profiles to facilitate its use, i.e., the product designer, the product architect, the process planner, the material expert. Based on DL language, the ontology is presented formally, and the above cited profiles are defined to facilitate knowledge extractions and ontology understanding.

This approach to design for 4DP is moving from a strict sequential organisation logic of marketing / study / industrialization / manufacturing actors to an integrated sense of simultaneous cooperation between all the product actors. The objective of these new organisational methods is to design concurrently a product efficient and harmonious on the different axes delineated by the main actors' needs.

3.1 Ontology Implementation

In this section, the implementation of the ontology (knowledge base for 4DP domain) is described. Respecting the defined framework in the last section, information are gathered such as AM techniques and materials related knowledge, and especially ad-hoc experiences presented in different research works.

The ontology is built upon top-down and bottom-up constructions strategies. The main goal is to formalise and describe a design for 4D printing knowledge, which needs mapping concepts and properties as presented in Fig.2. Protégé 5.5 software was used for this purpose. Hence, the upper classes (Additive_manufacturing_operation, Additive_manufacturing_process, Embedded_part, Geometry, Homogeneous_part, Hybrid_part, Machine, Material, Material_distribution, Mechanical_property,

process_condition, Stimulus, Product, Technical_function, Transformation_function, Transformation_dimension, Transformation_effect, Transformation_process, Transformation-step) are defined under the top class named “Thing” in Protégé software. As mentioned in the literature, the ontology was implemented respecting A-box and T-box: grey rectangles stand for the classes and hatched lines present mainly the object properties between classes.

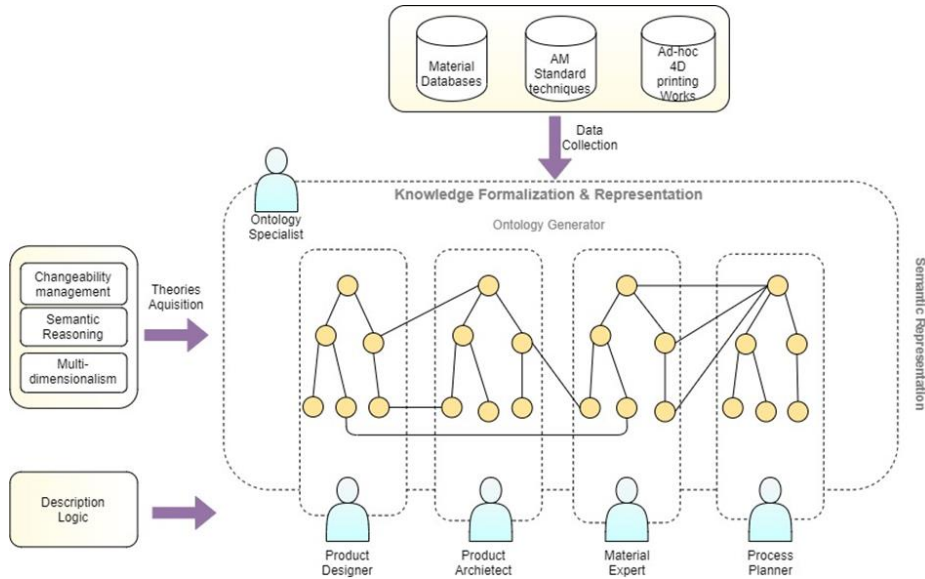


Fig. 1. Framework

A product can represent here the 4D printed part within its multiple states. The Embedded_part is a separate manufactured part generally added while the AM process to trigger the transformation. Homogeneous_part is printed with exclusively one material, however, the Hybrid_part is printed with at least two materials. The Voxel class is an elementary volume arranged and spaced in a Voxel_grid which has different data properties. It enables to decompose a 3D object in multiple sub-objects.

Then, the Transformation_function(s) are capitalised into six main primitives: Folding, Bending, Twisting, Expansion/Contraction, State_changing and Chemical_properties_changing. The latter is about a shifting in colour, mechanical properties ...etc. And State_changing stands for the changement of the material state (liquid/solid). Transformation_dimension captures the dimensional natures of the transformations' states (e.g., 1D to 1D, 1D to 2D, 1D to 3D, 2D to 2D, 2D to 3D, 3D to 3D). Transformation_effect presents the cycle of transformability like One_way which the change of the original shape/ property to a permanent one. Also, we can invoke Reversible (i.e. two ways) and Repeatable (i.e. more than two ways). Transformation_function is fulfilled by a Transformation_process which has a set of Transformation_step(s) (i.e. Training which limited to one Constrained_thermo_mechanics mechanism,

Stimulation which consists in applying the trigger(s) and Actuation is the main act of shifting that a 4D printed part fulfils.

Besides, a material class can have Mechanical_property(ies), Technical_function (Active_material (i.e., Actuator, Sensor, Transducer) , Sacrificial_material and Structural_material) and distributed with specific Material_distribution (Bilayer, Gradient, Uniform, Special_pattern). The latter exhibits spatial distribution patterns of smart (i.e. Active) and inert (i.e. Structural or Sacrificial) Materials. Stimulus class englobes the numerical and qualitative information that a Stimulus can bear to trigger such a material and consequently a 4D printed part. It can be: Chemical_structure, PH, Electric-charge, Magnetic_charge, Temperature, Mechanical_stress, Moisture, Heat and Light. Therefore, a stimulus triggers the Active_material and the _Object_aggregate, affects the Geometry and the Mechanical_property and enables the Transformation_function.

Finally, Additive_manufacturing_process class is already formalised by the "American society for testing and materials" and classified into seven major categories: Material_extrusion, Material_jetting, VAT_polymerisation, Binder_jetting, Direct_energy_deposition, Powder_bed_fusion, Sheet_lamination. And in the same context, Process_condition class specifies machine control parameters.

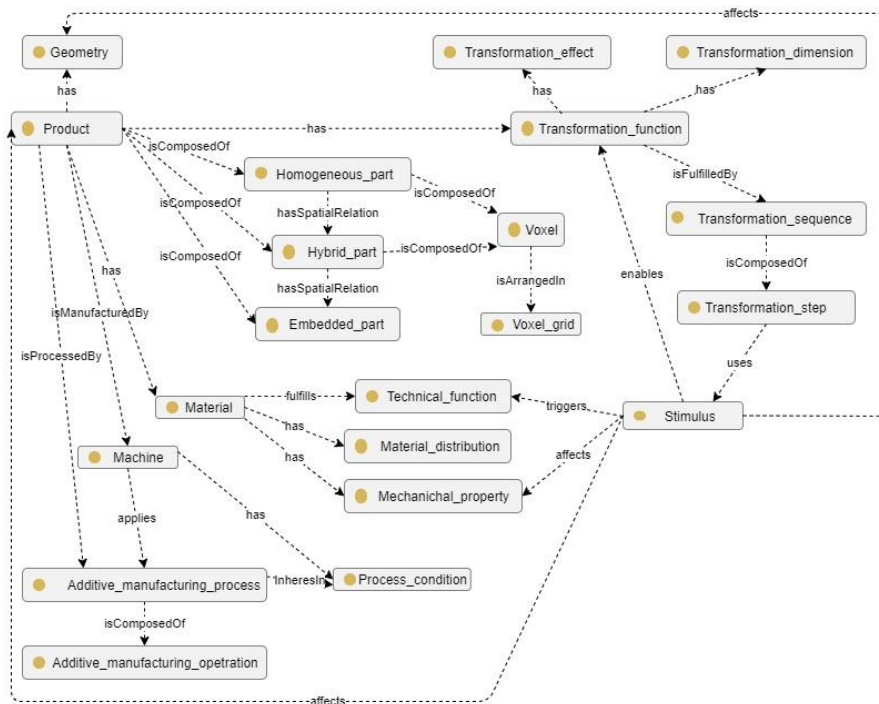


Fig.2. The proposed ontology graph for capitalising 4DP knowledge

3.3 Description Logic Language

Some of the ontology inheritances, object properties and data properties (like bending torque or angle) are presented as follows and respecting these definitions:

\sqsubseteq For describing the equivalent definition of the class

\forall Universal restriction

\exists Existential restriction

\sqcap Intersection between axioms

```

Product  $\sqsubseteq$  ( $\forall$  isComposedOf.Hybrid_part  $\sqcap$   $\exists$  isComposedOf.Homogeneous_part  $\sqcap$ 
 $\exists$  isComposedOf.Embedded_part)
Homogeneous_part  $\sqsubseteq$  ( $\forall$  isComposedOf.Voxel  $\sqcap$   $\forall$  hasSpatialRelation.Hybrid_part)
Hybrid_part  $\sqsubseteq$  ( $\forall$  isComposedOf.Voxel  $\sqcap$   $\exists$  hasSpatialRelation.Embedded_part)
Voxel  $\sqsubseteq$  (isArrangedIn = 1 Voxel_grid  $\sqcap$  has = 1 Position  $\sqcap$  has = 1 Color)
Product  $\sqsubseteq$  ( $\forall$  has.Geometry  $\sqcap$   $\forall$  has.Transformation_function  $\sqcap$   $\forall$  hasMaterial.Material
 $\sqcap$  isManufacturedBy = 1 Machine  $\sqcap$   $\forall$  isProcessedBy.Additive_manufacturing_process)
Transformation_function  $\sqsubseteq$  ( $\forall$  isComposedOf.Technical_function
 $\sqcap$  hasTransformationDimension = 1 Transformation_dimension
 $\sqcap$  hasTransformationEffect = 1 Transformation_effect  $\sqcap$   $\forall$  isFulfilledBy.Transformation_process)
Bending  $\sqsubseteq$  Transformation_function
Bending  $\sqsubseteq$  (has = 1 Bending_torque  $\sqcap$  has = 1 Bending_radius)
Twisting  $\sqsubseteq$  Transformation_function
Twisting  $\sqsubseteq$  (has = 1 Twisting_angle)
Folding  $\sqsubseteq$  Transformation_function
Folding  $\sqsubseteq$  (has = 1 Folding_torque  $\sqcap$  has = 1 Folding_angle)
Transformation_process  $\sqsubseteq$  isComposedOf = 1 Transformation_step
Stimulus  $\sqsubseteq$  ( $\forall$  triggers.Product  $\sqcap$   $\forall$  affects.Geometry  $\sqcap$  enables = 1 Transformation_process
 $\sqcap$   $\forall$  triggers.Material  $\sqcap$   $\forall$  affects.Mechanical_property)
Material  $\sqsubseteq$  ( $\forall$  fulfils.Technical_function  $\sqcap$ 
 $\forall$  hasMechanicalProperty.Mechanical_property  $\sqcap$ 
hasMaterialDistribution = 1 Material_distribution  $\sqcap$ 
isTriggeredBy = 1 Stimulus)
Machine  $\sqsubseteq$  ( $\forall$  has.Process_condition  $\sqcap$  applies = 1 Additive_manufacturing_process
 $\sqcap$   $\forall$  manufactures.Product)
Process_condition  $\sqsubseteq$  (inheresIn = 1 Additive_manufacturing_process)
Additive_manufacturing_process  $\sqsubseteq$  Process Additive_manufacturing_process  $\sqsubseteq$  (isAppliedWith = 1 Machine
 $\sqcap$   $\forall$  creates.Product)

```

For the sake of clarity, the sub-ontology (view) for only two user profiles is defined following the definitions below:

Top classes are listed in *Concept Set* s_{ci}

Object properties are listed in *Concept Subsumption* \leq_{ci}

Data types are listed in *Data Type Set* s_T

Data attributes are listed in *Data Attribute Set* s_A

Data properties are listed in *Data Properties Set* s_A

Definition of and object property between two to concepts ρ_R

Intersection of concepts \cap_C

- As for the product designer:

Concept Set $s_{c1} = \{ \text{TopConcept, Product, Homogeneous_part, Hybrid_part, Voxel, Voxel_grid, Geometry, Transformation_function, Embedded_part} \}$

Concept Subsumption $\leq_{c1} = \{ (\text{Top_concept, Product}), (\text{Top_concept, Homogeneous_part}), (\text{Top_concept, Hybrid_part}), (\text{Top_concept, Voxel}), (\text{Top_concept, Voxel_grid}), (\text{Top_concept, Geometry}), (\text{Top_concept, Transformation_function}), (\text{Top_concept, Embedded_part}), (\text{Embedded_part, Film}), (\text{Embedded_part, Electronic_component}), (\text{Object, Voxel}), (\text{Object, Embedded_part}), (\text{Object_aggregate, Hybrid_part}), (\text{Object_aggregate, Homogeneous_part}), (\text{Object_aggregate, assembly}), (\cap_C(\text{Voxel}, \rho_{VR}(\text{isArrangedIn, Voxel_grid, Object})), (\cap_C(\rho_{ER}(\text{has, Object}), \text{Geometry})), (\cap_C(\rho_{ER}(\text{has, Object}), \text{Transformation_function})), (\cap_C(\rho_R(\text{isComposedOf, Homogeneous_part}), \text{Voxel})), (\cap_C(\rho_R(\text{isComposedOf, Hybrid_part}), \text{Voxel})), (\cap_C(\rho_R(\text{isComposedOf, Assembly}), \text{Homogeneous_part})), (\cap_C(\rho_R(\text{isComposedOf, Assembly}), \text{Hybrid_part})), (\cap_C(\rho_R(\text{isComposedOf, Assembly}), \text{Embedded_part})), (\cap_C(\rho_R(\text{hasSpatialRelation, Homogeneous_part}), \text{Hybrid_part})), (\cap_C(\rho_R(\text{hasSpatialRelation, Hybrid_part}), \text{Embedded_part})),$

$(\rho_{VA}(\text{Position, xsd: decimal}), \text{Voxel}), (\rho_{VA}(\text{Color, xsd: string}), \text{Voxel}),$

$(\rho_T(\text{Initial_state, xsd: string}), \text{Object}), (\rho_T(\text{Final_state, xsd: string}), \text{Object}) \}$

DataType Set $s_T = \{ \text{TopDataType, Initial_state, Final_state} \}$

DataAttribute Set $s_A = \{ \text{TopDataAttribute, Color, Position} \}$

DataProperties Set $s_A = \{ \text{TopDataProperty, isComposedOf, hasSpatialRelation, has, isArrangedIn} \}$

- As for the product Architect:

Set of top concepts $s_{c4} = \{ \text{TopConcept, Transformation_function, Transformation_process, Transformation_step, Transformation_effect, Transformation_dimension} \}$

Concept Subsumption $\leq_{c4} = \{ (\text{Top_concept, Transformation_function}), (\text{Top_concept, Transformation_process}), (\text{Top_concept, Transformation_step}), (\text{Top_concept, Transformation_effect}), (\text{Top_concept, Transformation_dimension}), (\text{Transformation_function, Bending}), \dots, (\text{Bending, Buckling}), (\text{Transformation_step, Training}), \dots, (\text{Training, Constrained_thermo_mechanical}), (\cap_C(\text{Transformation_function, } \rho_R(\text{isFulfilledBy, Transformation_process}))),$

$(\cap_C(\text{Transformation_function, } \rho_R(\text{hasTransformationEffect, Transformation_effect}))),$

$(\cap_C(\text{Transformation_function, } \rho_R(\text{hasTransformationDimension, Transformation_dimension}))),$

$(\cap_C(\text{Transformation_function, } \rho_R(\text{isComposedOf, Technical_function}))), (\cap_C(\text{Transformation_process } \rho_R(\text{isPartOf, Transformation_step}))), (\cap_C(\text{Stimulation } \rho_R(\text{uses, Stimulus}))), (\rho_T(\text{Bending_torque, xsd: decimal}), \text{Bending}), (\rho_T(\text{Bending_radius, xsd: decimal}), \text{Bending}), (\rho_T(\text{Twisting_angle, xsd: decimal}), \text{Twisting}), (\rho_T(\text{Folding_angle, xsd: decimal}), \text{Folding}), (\rho_T(\text{Folding_torque, xsd: decimal}), \text{Folding}) \}$

DataProperties Set $s_A = \{ \text{TopDataProperty, isPartOf, uses, isFulfilledBy, isComposedOf, hasTransformationDimension, hasTransformationEffect} \}$

DataType Set $s_T = \{ \text{Bending_Torque, Bending_radius, Twisting_angle, Folding_angle, Folding_torque} \}$

Set of Instances $s_I = \{ \ll 1D_to_1D \gg, \ll 1D_to_2D \gg, \ll 1D_to_3D \gg, \ll 2D_to_2D \gg, \ll 2D_to_3D \gg, \ll 3D_to_3D \gg, \ll One_way \gg, \ll Reversible \gg, \ll Repeatable \gg \}$

Set of Concept Instantiation $i_c = \{ (\text{Transformation_dimension, 1D_to_1D}), (\text{Transformation_dimension, 1D_to_2D}), (\text{Transformation_dimension, 1D_to_3D}), (\text{Transformation_dimension, 2D_to_2D}), (\text{Transformation_dimension, 2D_to_3D}), (\text{Transformation_dimension, 3D_to_3D}), (\text{Transformation_effect, One_way}), (\text{Transformation_effect, Reversible}), (\text{Transformation_effect, Repeatable}) \}$

Hence, the proposed ontology is formalised and the presented knowledge is theoretically extracted for the product designer and the product architect for facilitating the future usage and restricting the upload of unnecessary classes or object properties for a user profiles who doesn't need them.

4 Use Case: Deployable Satellite

A deployable satellite prototype with four solar panels executing an unfolding transformation from an initial folded state (Fig.3 (a)) to a final completely unfolded state (Fig.3(b)) is presented as a case study to demonstrate the applicability of the developed ontology. The consistency of ontology is checked in the protégé software using HermiT reasoner. It is about describing and formalizing the knowledge behind this 3D-to3D transformation. The objective here to capture relevant knowledge ensuring the transformation from a *Folded_structure* to an *Unfolded_structure*. The ontology presented in the latter section is manually populated which has led to an instance graph represented in Fig6. For sake of clarity and in order to avoid repetition, the deployable satellite ontology is presented in modular format. Since, it has four similar legs of solar panels which involves parts with active and inert materials, only one leg is described in Fig.4. As a fragment of the module of Homogeneous and hybrid parts. The parts are topologically connected with *isTangentTo* relation. Also, the transformation steps of each smart hinge in one leg and of the four legs are quite similar, that's why the transformation process of only one leg of solar panels is captured in the Fig.5 as a fragment of the module of transformation steps. Each hinge will be transformed in an unfolded one. This prototype is printed through a FDM machine respecting a set of universal and agreed conditions and operations. The material used is sensitive to temperature variations thus the technical function of this unfolding is thermoactive. As such, voxel class is not considered here because the material distribution of both active (*Panel0i_j*) and smart (*Hinge0i_j*) parts is uniform, hence there no need to decrease the geometrical representative level. Respecting the DL sets defined in the third sections, two views are manually extracted respecting the needs of the product designer (Fig.7) and product architect (Fig.8).

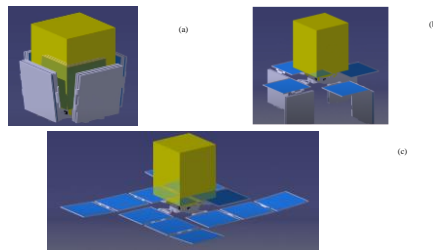


Fig.3. Deploying Satellite - Use Case (a) Initial State (b) Intermediary State (c) Folded State

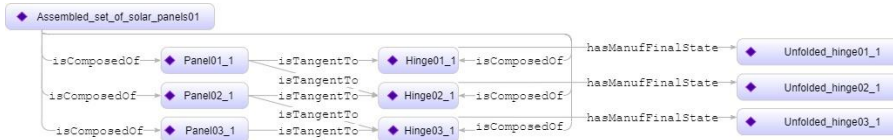


Fig.4. Fragment of the module of homogeneous & hybrid parts

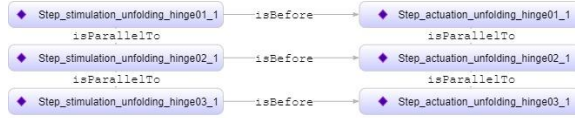


Fig.5. Fragment of the module of Transformation Steps

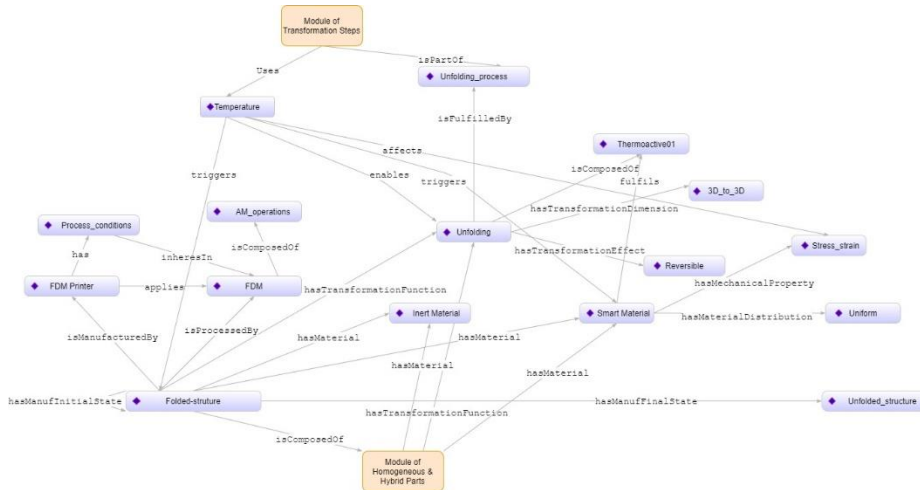


Fig.6. Intances graph capitalising the knowledge of 4DP in Deployable Satellite

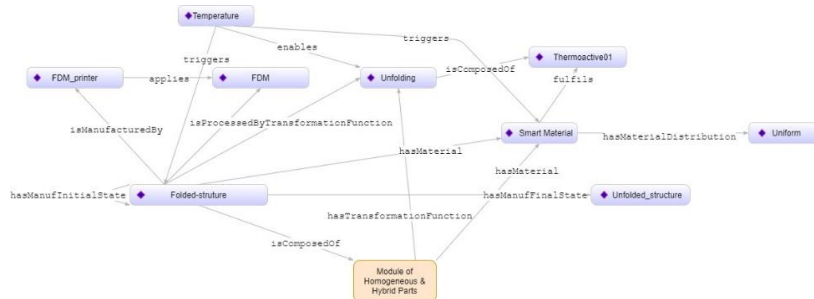


Fig.7. The design view for product designer

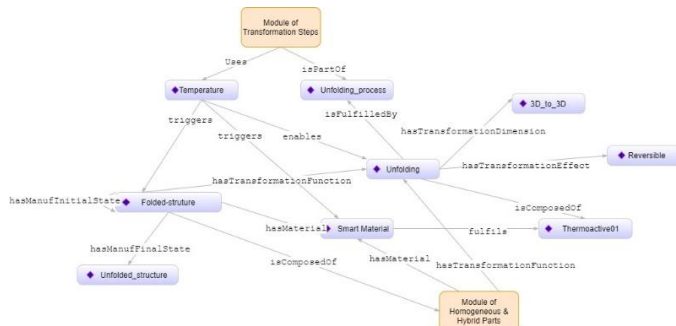


Fig.8. The transformation view for product architect

5 Conclusion & Future work

Our research has stressed the formalization and representation of 4DP knowledge relating AM processes and techniques, AMs, stimuli, and transformation matters. It therefore represents a pioneer effort towards knowledge federation and representation for multiple purposes aligned with a preliminary design phase. To do so, an ontological framework has been beforehand established with the underlying theories (mereotopology, AM knowledge, material knowledge, ontology changeability) along with the use of 4DP knowledge in design. The proposed ontology includes reasoning capabilities supported by DL rules. These rules have permitted the formal definition of the proposed ontology and the theoretical extraction of views according to a preliminary users' needs. However, additional reasoning layers will be needed to fully capture 4DP knowledge over views. A deployable satellite is presented as a case study to capture the knowledge behind a triggered unfolding transformation and two sub-ontologies are presented respecting the DL formalization to prove that the views are extracted within the adequate user profile. For example, for the product designer, the module of transformation steps and planification is omitted from the graph regarding the fact that it is the product architect's job.

For instance, future work is presented in Fig.9 as perspectives projecting possible approaches after implementing the 4DP ontology. A dedicated API is about to make the ontology and its whole axioms readable by a specific CAD software (e.g., Grasshopper as a plug-in of Rhinoceros). Hence, a structured library is ready for use for the different four actors with multiple purposes. A cognitive prediction of the transformations sequence is envisaged through machine learning (ML) tools based on the reuse of ad-hoc experiments as a learning data. Hence an appropriate CAD tool is ready to automatically generate 3D CAD geometric models, i.e., functional and fabricable three-dimensional geometric shapes. And then, the simulation engineer can take profit from the created geometric inference engine.

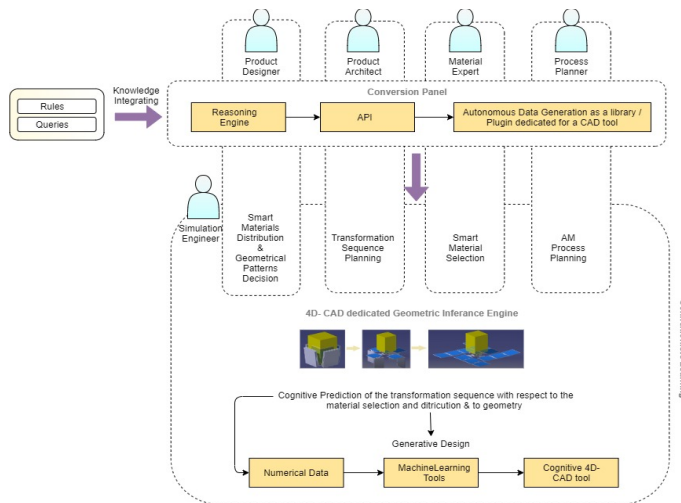


Fig.9. Proposed Perspectives

Acknowledgements

This research activity is part of a much larger project in the field of design for 4D printing. The authors would like to thank the French Ministère de l'Enseignement Supérieure et de la Recherche, the French “Investissements d'Avenir” program, project ISITE-BFC (contract ANR- 15-IDEX-0003) as main financial supports of this research program, and S. mart Franche-Comté network for their participation.

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