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A CATEGORICAL FRAMEWORK IN ADDITIVE MANUFACTURING

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Abstract

Additive manufacturing (AM) changes the way products are designed, manufactured and measured. It enables the fabrication of components with complex geometries and customisable material properties. However traditional design rules or guidelines are no longer applicable for AM. As a result design for additive manufacturing lacks of formal and structured design principles and guidelines. It urges a comprehensive system that can help designers and engineers understand for example how the geometrical design and process parameters will affect each other, and how to configure process parameters to meet specifications. In this paper a set of category ontologies has been developed to formalise fundamental/general knowledge of design and process for AM. A collection of design guidelines and rules are encapsulated and modelled into categorical structures. The formalisation of knowledge of AM will enable existing fundamental/general knowledge of AM process and state-of-the-art designing cases computer-readable and to be interrogated and reasoned, and then can be integrated into CAx platforms.

Keywords: Additive Manufacturing (AM), geometrical variability, process parameters

1. Introduction

Additive manufacturing (AM) changes the way products are designed, manufactured and measured. It enables the fabri- cation of components with complex geometries and customis- able material properties. However traditional design rules and guidelines are no longer applicable for AM. In the past most research and development efforts in AM have been focused on new powder materials and process development. Much of the existing knowledge body is build upon empirical principles and experimental research [1]. As a result many currently available AM design guidelines are highly machine-specific or material- specific [2]. Also the guidelines often fail to provide compre- hensive information that can help designers understand the ca- pabilities and limitations of various type of AM processes, how the geometrical design and process parameters will affect each other, and how to configure process parameters to meet specifi- cations. Driven by design functionality, the focus of design for AM (DfAM) has been gradually shifted from process focused guidelines to more integrated process-geometry design guide- lines in recent years. As current DfAM lacks of formal and structured design principles and guidelines, it urges a compre- hensive system that can provide fundamental and general de- sign and process control guidelines to aid with decision making. To start with, AM knowledge has to be formalised first to be machine-readable and to enable knowledge reasoning and interrogation. With a proper interface, the formalised knowledge can then be captured, accessed and interrogate by AM design- ers/engineers to help with decision making regarding product specification, supporting structures, process parameters, etc.

The current state-of-the-art for formalising AM knowledge is based on descriptive logics (DLs) to construct different AM ontologies such as design ontology [3,4] and process ontology [5,6]. In each ontology, a set of entities and relation between entities were established to help AM designers or engineers identify relationships and interconnectivity between different parameters. DLs are based on set theory and are best suited to represent relationships between sets. They are therefore limited in extent (no sets of sets) and cannot directly merge two dif- ferent ontologies, nor construct complex relationships among ontologies. In this paper the knowledge modelling is based on category theory and the modelling method is updated from authors' previous work [8,9] with redefined syntax and seman- tics. The categorical-base

2. Category Ontology

In this section, a brief introduction of category ontology in which objects, morphisms and morphism structures are intro- duced. As the knowledge modelling method is entirely inde- pendent with AM, some readers may find it disconnect with the following section. However the foundation of the knowledge modelling has to be represented first otherwise the knowledge structure in the following section can not be understood.
A category ontology C is denoted by a triple (N_O, N_M, N_S), where N_O is a set of objects, N_M is a set of morphisms and N_S is
a set of morphism structures. All objects and morphisms satisfy the set of category laws.

Objects Let A be an object in $\mathcal{C}$, it may also be one of five special type of objects with extra properties, written as $A.p$, where $p ::= t \mid i \mid z \mid s \mid e$. The five types are: terminal object (denoted as t), initial object (i), zero object (z), singleton object (s) and empty object (e).

Morphisms A morphism represents a relationship from ob- ject A to B in C, written as $f : A \rightarrow B$. Here A is the domain of f, denoted $A = f(O1)$ and B is the codomain of f, written as $B = f(O2)$. A morphism set represents all morphisms from objects A to B in C, written as $M(A, B)$. For any object $A \in$ C.N_O, there is an identity morphism on object A, denoted as $id(A)$.

A morphism f may also has one of six special properties, written as $f.p$, where p can be null (a morphism may not have any properties), epic (denote as --->), monic (↣), isomorphic (↔), retraction (●→), section (•→), both epic and monic but not isomorphic (↣-->), as shown in Table 1. A morphism can only have at most two properties. The properties of a morphism is of significant importance both to generate results from reason- ing rules, and to help end-users to understand the nature of the relationship.
Also a morphism f is often assigned with a notion to make it readable, written as $f : A(notion) \rightarrow B$. Notions of a morphism could be started with characters such as 'is', 'has', 'with' and 'applied to'.

Morphism structures Six morphism structures, including product structures (×), coproduct structures (u), triangle struc- tures (△), rectangle structures (o) and pullback/pushout structures (∏; Li) are redefined based on categorical concepts with enriched details and more deduced structures. Note that a mor- phism structure allows nesting of other morphism structures.
Product structure $\times(O1, O2, p1, p2)$ is constructed by a product of two objects $O1$ and $O2$, and two projection morphisms $p1$ and $p2$, where $p1 : O1 \times O2 \rightarrow O1$, $p2 : O1 \times O2 \rightarrow O2$. If there is another object $O3$ has two project morphisms f and g, where
$f : O3 \rightarrow O1$, $g : O3 \rightarrow O2$, there exists a unique morphism
$u : O3 \rightarrow O1 \times O2$, and $p1 \circ u = f$, $p2 \circ u = g$.

Table 1: Special properties of morphism f

Constructor	Synatx	Semantics
Epic	$f : A \twoheadrightarrow B$	$\forall A, B, C \in \mathcal{C}.N_O, g : B \rightarrow C,$ $h : B \rightarrow C, \{g \circ f = h \circ f\} \Rightarrow g = h$
Monic	$f : A \rightarrowtail B$	$\forall A, B, C \in \mathcal{C}.N_O,\ g : A \rightarrow B,$ $h : A \rightarrow B, \{f \circ g = f \circ h\} \Rightarrow g = h$
Isomorphic	$f : A \leftrightarrow B$	$\forall A, B \in \mathcal{C}.N_O, f : A \leftrightarrow B.$ $\exists f^{-1} : B \rightarrow A, f^{-1} \circ f = id(A),$ $f \circ f^{-1} = id(B)$
Retraction	$f : A \bullet\!\!\rightarrow B$	$\forall A, B \in \mathcal{C}.N_O,\ \exists f^{-1} : B \rightarrow A,$ $f \circ f^{-1} = id(B)$
Section	$f : A \blacksquare\!\!\rightarrow B$	$\forall A, B \in \mathcal{C}.N_O,\ \exists f^{-1} : B \rightarrow A,$ $f^{-1} \circ f = id(A)$
Epic&Monic	$f : A \rightarrowtail\!\!\!\twoheadrightarrow B$	$\forall A, B \in \mathcal{C}.N_O.\ f : A \twoheadrightarrow B \& f : A \rightarrowtail B$ $\& !f : A \leftrightarrow B$

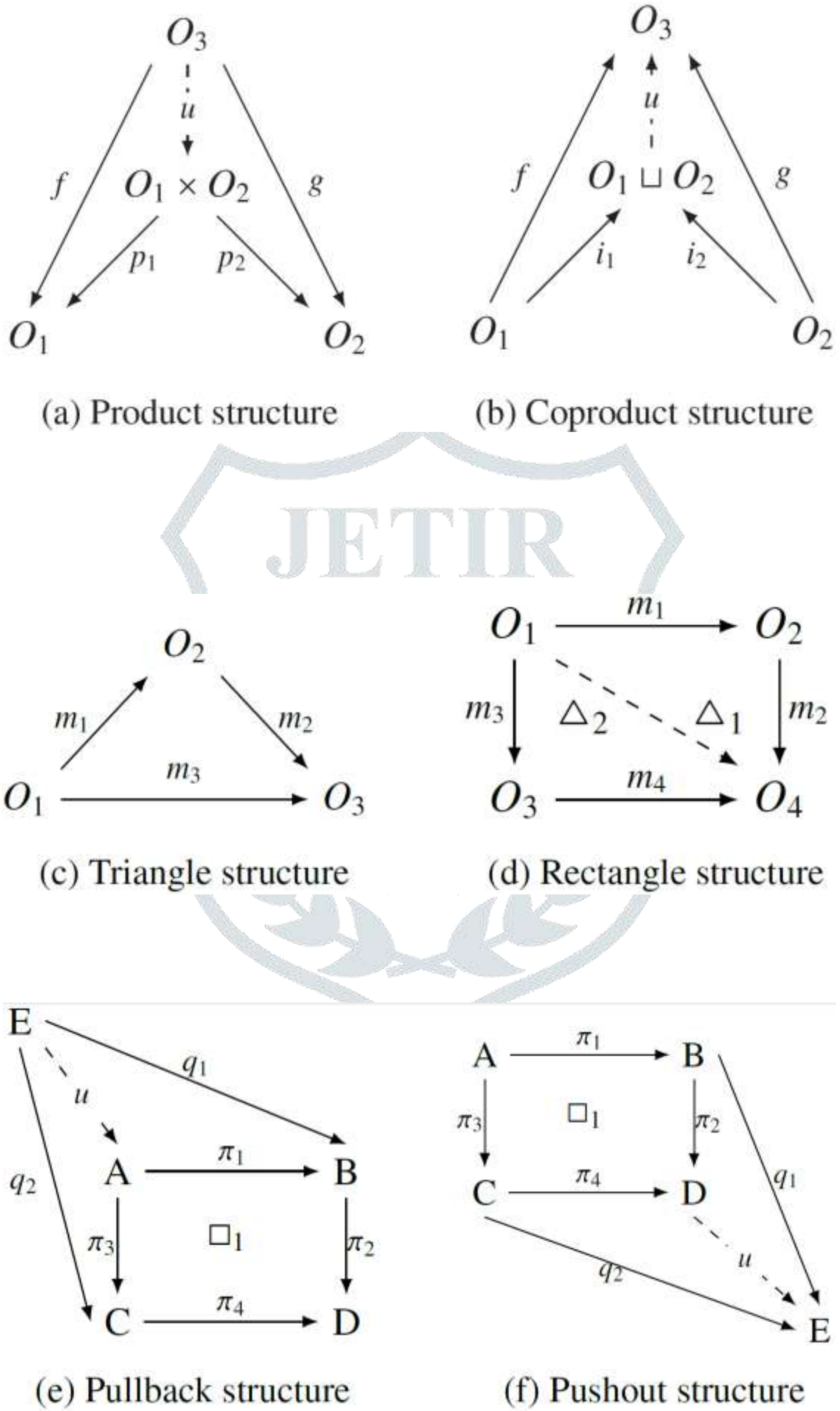

Fig. 1: Morphism structures

Coproduct structure $\cup(O1, O2, i1, i2)$ is constructed by a co- product of two objects $O1$ and $O2$, and two inclusion morphisms
$i1$ and $i2$, where $i1 : O1 \rightarrow O1 \cup O2$, $i2 : O2 \rightarrow O1 \cup O2$. If there
is an object $O3$ with two inclusion morphisms $f : O1 \rightarrow O3$, $g : O2 \rightarrow O3$, there exists a unique morphism $u : O1 \cup O2 \rightarrow O3$, and $u \bigcirc i1 = f$, $u \bigcirc i2 = g$. More details about product and co-
product in category theory can refer to [7].

Triangle structure $\triangle(\{O1, O2, O3\}, \{m1, m2, m3\})$ is formed by two commutative morphism $m1$ and $m2$ in between three objects $\{O1, O2, O3\}$ and a composition morphism of the two
$m3 = m2 \bigcirc m1$. In this paper, the first object $O1$ of a triangle structure is denoted as $\triangle(O1)$, the second object as $\triangle(O2)$, and the third object as $\triangle(O3)$, so does for the morphisms of a triangle structure, written as $\triangle(m1)$, $\triangle(m2)$ or $\triangle(m3)$.

Rectangle structure $o(\{O1, O2, O3, O4\}, \{m1, ..., m4\}, \Delta 1, \Delta 2)$ is formed by four morphisms and four objects, which also form two triangle structures $\triangle 1(\{O1, O2, O4\}, \{m1, m2, m1 \circ m2\})$ and $\triangle 2(\{O1, O3, O4\}, \{m3, m4, m3 \circ m4\})$, such that $\Delta 1(m1) = o(m1)$, $\Delta 1(m2) = o(m2)$, $\Delta 2(m1) = o(m3)$, $\triangle 2(m2) = o(m4)$. And $o(O1)$ is the staring object of the rectangle structure and $o(O4)$ is the ending object.

Pullback structure $\prod(\{O1, ..., O5\}, \{m1, ..., m9\}, \{o1, ..., o4\})$ is constructed from a rectangle structure $o1$ in which $o1(\triangle 1(m2))$ or $o1(\triangle 2(m2))$ is either monic or isomorphic. It consists of a set of five objects and a set of nine morphisms whose objects and morphisms form four rectangle structures including $o1$. The four rectangle structures are listed as follows:

$o1(\{A, B, C, D\}, \{\pi1, \pi2, \pi3, \pi4\}, \Delta 1, \Delta 2)$,
$o2(\{E, B, C, D\}, \{q1, \pi2, q2, \pi4\}, \Delta 3, \Delta 4)$,
$o3(\{E, A, C, D\}, \{u, \pi4 \circ \pi3, q2, \pi4\}, \Delta 5, \Delta 4)$,
$o4(\{E, B, A, D\}, \{q1, \pi2, u, \pi4 \circ \pi3\}, \Delta 3, \Delta 5)$,
where
$\triangle 1(\{A, B, D\}, \{\pi1, \pi2, \pi2 \circ \pi1\})$,
$\triangle 2(\{A, C, D\}, \{\pi3, \pi4, \pi4 \circ \pi3\})$,
$\triangle 3(\{E, B, D\}, \{q1, \pi2, \pi2 \circ q1\})$,
$\triangle 4(\{E, C, D\}, \{q2, \pi4, \pi4 \circ q2\})$,
$\triangle 5(\{E, A, D\}, \{u, \pi4 \circ \pi3, \pi4 \circ \pi3 \circ u\})$ in which two morphisms ($\pi4 \circ \pi3$ and $\pi4 \circ \pi3 \circ u$) are deduced from the composition rule.

Apart from $o1$, other rectangle structures (can be also written as o') all start with object E and end with object D. For any o', morphisms u, $\pi3$ and $q2$ always form a triangle structure $\triangle 6(u, \pi3, q2)$, so do morphisms u, $\pi1$ and $q1$ form $\triangle 7(u, \pi1, q1)$.

Pushout structure $\mathrm{U}(\{O1, ..., O5\}, \{m1, ..., m9\}, \{o1, ..., o4\})$ is constructed from a rectangle structure $o1$ in which $o1(\triangle 1(m1))$ or $o1(\triangle 2(m1))$ is either epic or isomorphic. It
consists of a set of five objects and a set of nine morphisms, whose objects and morphisms form four rectangle structures
including $o1$. The four rectangle structures is listed as follows:

$o1(\{A, B, C, D\}, \{\pi1, \pi2, \pi3, \pi4\}, \Delta 1, \Delta 2)$,
$o2(\{A, B, C, E\}, \{\pi1, q1, \pi3, q2\}, \Delta 3, \Delta 4)$,
$o3(\{A, B, D, E\}, \{\pi1, q1, \pi2 \circ \pi1, u\}, \Delta 3, \Delta 5)$,
$o4(\{A, D, C, E\}, \{\pi4 \circ \pi3, u, \pi3, q2\}, \Delta 5, \Delta 4$,
where
$\triangle 1(\{A, B, D\}, \{\pi1, \pi2, \pi2 \circ \pi1\})$,
$\triangle 2(\{A, C, D\}, \{\pi3, \pi4, \pi4 \circ \pi3\})$,
$\triangle 3(\{A, B, E\}, \{\pi1, q1, q1 \circ \pi1\})$,
$\triangle 4(\{A, C, E\}, \{\pi3, q2, q2 \circ \pi3\})$,

$\triangle 5(\{A, D, E\}, \{\pi 2 \circ \pi 1, u, u \circ \pi 2 \circ \pi 1\})$.

All rectangle structures in the pushout structure start with object A apart from o1, the other rectangle structures (o′) all end with object E. For any o′, morphisms $\pi 2$, u and $q1$ always form a triangle structure $\triangle 6(\pi 2, u, q1)$, so do $\triangle 7(\pi 4, u, q2)$.

3. AM design and process category ontologies

In this section, general AM design and process knowledge will be structured into two sets of category ontologies respec- tively. Mappings between the two sets will then be established, that is a set of functors (relationship from one category ontology to another) between the two sets. One of the AM technologies, powder bed fusion (PBF) is selected for the purpose of process modelling.

3.1 *Design category ontology*

To structuralise the design knowledge, different types of de- signing parameters such as geometrical variability, feature designs including overhanging and extrusion features, and sup- port structures are constructed into a category ontology *Design Parameters* (D*P*) . Objects in the category ontology and morphisms between these objects are then defined as shown in Fig.

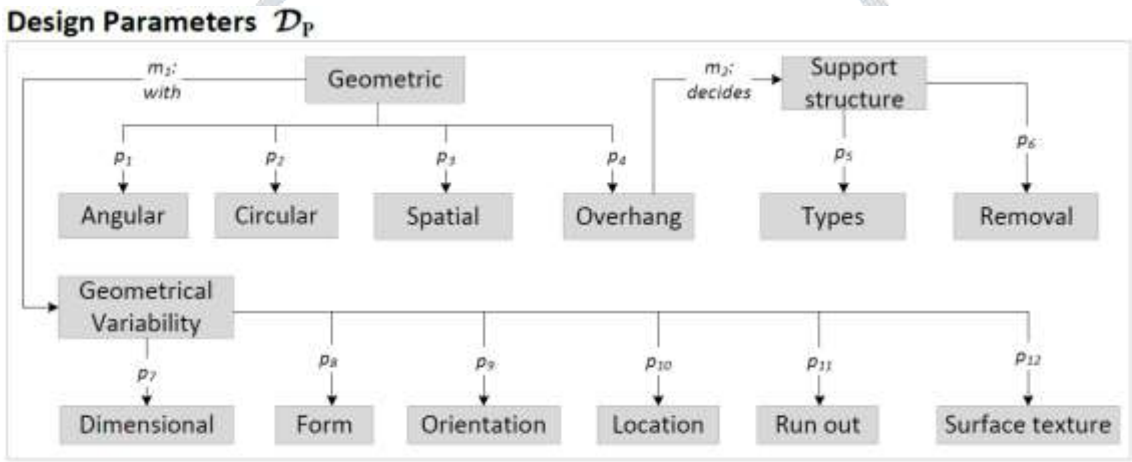

Fig. 2: AM design category ontology $\mathcal{D}_P$

2. Here, D*P*

encloses three nested product structures, where
object [Geometric] is a product object from [Angular], [Circular], [Spatial] and [Overhang]; [Support Structure] is a product object from [Types] and [Removal]; [Geometrical Variability] is a product object from [Dimensional], [Form], [Orientation], [Location], [Run out] and [Surface Texture].

Note that the objects in D*P* is non-inclusive, as more objects can be added to form more product structures ($\times i$). For example,
[Surface Texture] can also be a product object, if more surface texture related objects are added into D*P*. These objects are however not included in this paper as there is yet no evidences of detailed relationships between these objects and objects in the following process category ontologies.
Different from traditional manufacturing processes, support structure is one of the critical designing parameters for AM to extract heat from the part and to provide mechanical anchor to avoid warpage due to thermal stresses during and after the build. The design of support structures is a process to optimise the volume, geometry, location and part-support interface ge- ometry. During the designing process, overhanging features, build orientation, GD&T and the easiness of removal have to be considered. For instance, when a overhanging feature is over 45 degree, or the feature has very large projected areas, a sup- port structure is normally required. Also the need of support structure can be reduced by changing the build

orientation, or by designing the support structure on where there is less geo- metrical accuracy requirements. Therefore there is a morphism m_2:[Overhang](*decides*) → [Support structure], and the prop- erty of m_2 is however not yet decidable.

3.2 Process category ontologies

For the process control parameters, the following category ontologies are constructed: *Environment* (P_{En}) represents the chamber environment elements; *Powder* (P_{Po}) states parame- ters of the powder; *Energy* (P_{Ee}) indicates the parameters of the AM power; and *Process Control* (P_{Pc}) encloses process pa- rameters as indicated in Fig. 3.

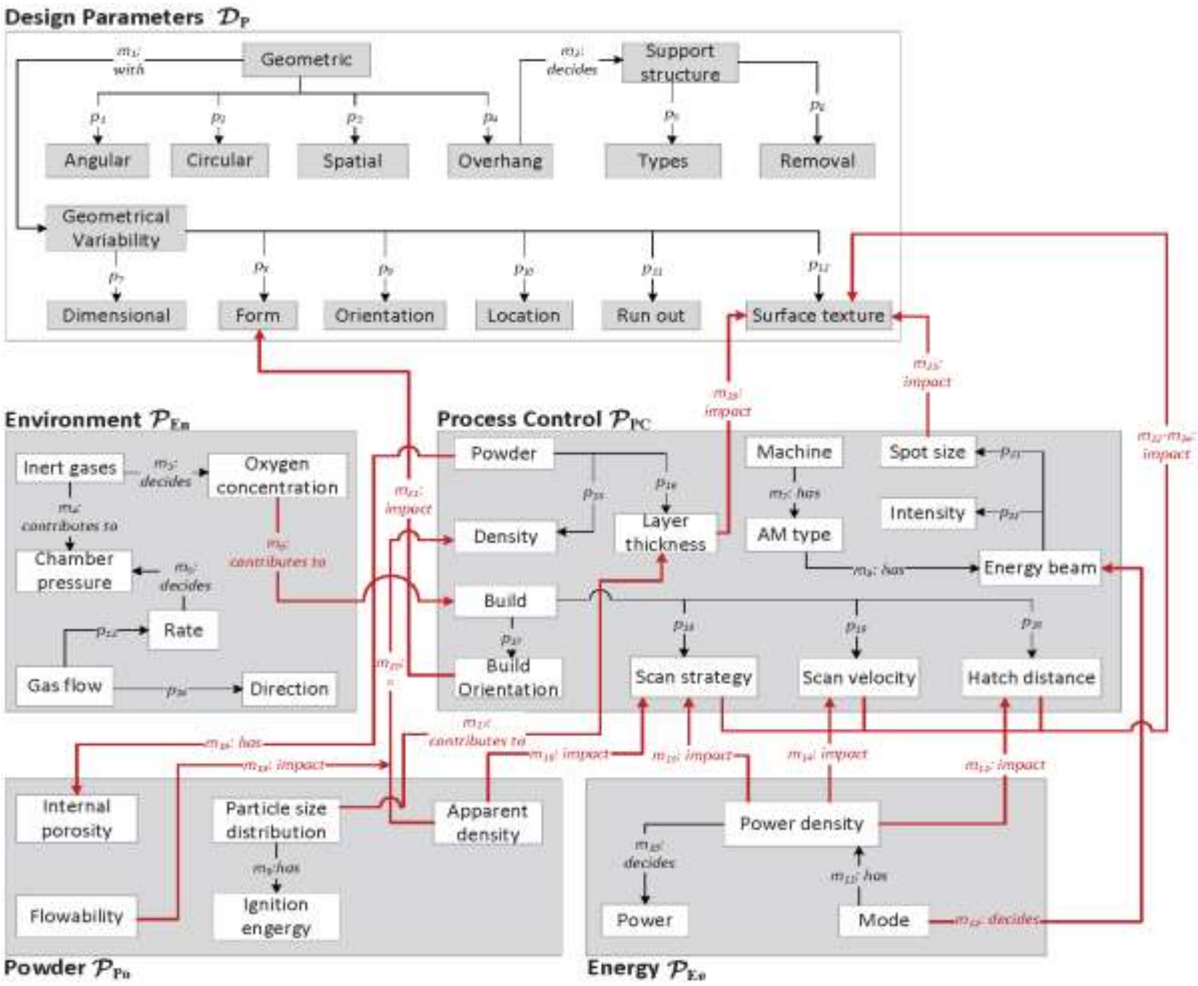

Fig. 3: AM design category ontology $\mathcal{D}_P$

Mappings between design and process category ontologies, can be established by finding relationships between objects in design category ontology and critical objects in process cate- gory ontologies. This can also help identify relationships and interconnectivity between different AM models and their pa- rameters. In the category ontology of *Process Control* (P_{Pc}), important process parameters including [Build orientation], [Scan strat- egy], [Layer thickness] and [Scan velocity] have critical impact on the GD&T of the fabricated AM part. The [Build orienta- tion] will impact the form accuracy, for example cylindricity [11]. Surface texture can be affected by the [Layer thickness], [Scan strategy], [Scan velocity], [Hatch distance] and energy beam [Spot size]. For example the setting of medium-high [Scan velocity] together with medium [Hatch distance] is ideal for growth aligning in the build direction and resulting in an isotropic build thus have a better [Surface texture] [12].

[Layer thickness] is correlated to the [Particle size distribu- tion] (in P_{Po}). Layer thickness is limited by the mean particle size of the powder and ideally it would be slightly larger than the mean particle size. Normally small [Layer thickness] may result in better [Surface texture]. Along the build direction (Z- direction), the [Layer thickness] is usually affect the [Geomet- rical variability] (in D_P). Thinner [Layer thickness] together with slower [Scanning velocity] when the total input [Power density] is held constant, will result in narrower track width and improved [Surface texture].

[Scan strategy] is closely related with beam diameter to al- low sufficient overlapping of adjacent paths occurs and prevent- ing partial melting. Most metal AM systems employ sophisti- cated scan strategies to reduce thermal residual stress which can affects the geometry variability. However it is still very difficult to predict accurately the thermal residual stress.
In the category ontology PEn, [Inert gases] such as nitrogen or argon are used to control the build chamber environment and maintain low [Oxygen concentration]. [Oxygen concentration] is closely related to the success of a build process and it is typ- ically maintained below 1-2%. For reactive material such as aluminium and titanium, oxygen content control is of critically importance for safety reasons.
In the category ontology PPo, [Particle size distribution] is closely related to the [Layer thickness] and thus affect [Surface texture] of the fabricated part. The powder [Flowability] will affect powder feeding and raking, and a better [Flowability] can achieve smoother powder layers. Also high [Apparent density] and no [Internal porosity] is preferred for the success of build.
In the category ontology PEe, the [Power density] is closely related to [Scan strategy], [Scan velocity] and [Hatch distance]. The powder [Mode] also decides the geometry of [Energy beam] and [Spot size].

4. Conclusion

In this paper a design category ontology and a set of PBF AM process category ontologies were constructed. Mappings between the two sets of category ontologies were also estab- lished to represent an abstract framework of AM design and process control. The proposed AM design and process category ontologies can be suited for formalising domain, state-of-the-art and experimental knowledge. With a proper interface, the struc- tured general AM knowledge can then be captured, accessed and interrogate by AM designers/engineers to understand links between different parameters. As this is an abstract framework, the objects in this framework are non-inclusive. More objects and morphisms are expected to identify in the future work. For example, if the designers have to deal with specific processes or specific systems, i.e. laser-based or electron beam-based processes, more specific process-oriented objects can be added into the existing category ontologies. The formalised knowl- edge can also serve as a training material to help designers and engineers understand the interconnection and complex relation- ships.
The properties of a morphism is of critical importance for relationship reasoning. As some of the morphisms' properties cannot be decided, it is desirable to update the properties of the constructed morphisms along with the development of AM technologies and customised case studies.

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