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A process classification framework for defining and describing Digital Fabrication with Concrete

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A B S T R A C T

Digital Fabrication with Concrete (DFC) encompasses 3D Concrete Printing (3DCP) and many other methods of production. DFC is emerging from an era of invention and demonstration to one where the merits of one principle over another needs to be quantified systematically. DFC technologies vary in characteristics, complexity and maturity which hampers the synthesis of research and comparisons of performance. The interdependence of design geometry, material properties and process characteristics is well recognised. Materials research has made significant progress in recent years and there have been many applications with varying design geometries demonstrated. Far less has been done to guide the definition and description of the processes used. This work takes a step forward by presenting classification and process description guidance for DFC. The approach was developed by engaging a broad cross-section of the international community through the activities of the RILEM Technical Committee 276 between 2016 and 2020.

1. Introduction

Large-scale Additive Manufacturing with cement-based mortars, commonly referred to as 3D Concrete Printing (3DCP) has, alongside many other digital fabrication methods, emerged worldwide in response to the global call to modernise construction manufacturing [1–3]. Digitally driven processes offer benefits of productivity which are not necessarily the replacement of hand operations by automation, but in the reduction of intermediate stages required in fabrication, such as the need for a mould [4]. In addition, DFC offers value added because it enables a significant amount of customisation in design with little if any increase of fabrication costs, as is the case with more conventional Additive Manufacturing processes [5].

'World's first' projects remain in the attention of the media and much of the work has been pioneered through entrepreneurial endeavour by start-up SMEs. There are many groups world-wide engaged in research and enterprise and large organisations are investing in the technology. Academic and industrial R&D partnerships continue to be established, and there is a proliferation of methods and approaches from the early work on fundamental concepts and applications in the mid-late 2000's [6] to the richer variety of process and applications found the contemporary field [7–13].

The international community has demonstrated a wide range of applications, but the field needs to move from *fabrication* (one off production) to *manufacturing* (routine production at volume). To do this, we need standardised approaches for testing and evaluating the factors that affect the performance of the manufacturing system and the materials used, in the context of the design and application of the product being manufactured. This is particularly important in the emerging field of DFC because the materials, process characteristics and maturity in development varies so widely. Standardised methods of measurement and reporting for materials exist and there is increasing clarity in the applications (and hence part geometries) that can be manufactured, however there is no commonly agreed framework for

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describing processes.

This paper presents a classification system that was developed over the last four years through the activities of the RILEM Technical Committee 276, 'Digital fabrication with cement-based materials'. It involved a significant number of the active DFC community in its development, through many hours of debate and exposure in public meetings and presentations to the wider research and industrial communities which included actors in construction and manufacturing. It provides a structured approach for identifying and describing differences between processes that serve to:

- educate those unfamiliar to the field;
- provide an approach to improve the description of processes in publications; and,
- underpin the development of standards.

2. Background

The first inter-process comparison was presented in [6] which identified the three methods that had been developed at that time against the process proposed by [14]: 3D Concrete Printing developed at Loughborough University (UK) used extrusion of cement mortar to manufacture fully dense parts, intended for implementation in a factory [6,15]; Contour Crafting developed at the University of Southern California (US) which (at the time) used extruded clay as a permanent former, backfilling the central section with conventional cast concrete perform a vertical wall intended to automate construction of wall elements in situ, on-site [16]; and the d-Shape (or Monolite, www.d-shape.com) process that used a particle bed of sand and jetted binder system, very similar in principle to the Zprinter by 3D systems. The principle descriptors used to differentiate the processes were: whether it was a permanent formwork or manufacturing the functional material; the type of build material and binder; nozzle number and diameter; layer thickness; whether reinforcement was used; the print dimensions and Pre/Post-processing operations. Common characteristics were presented as a Venn diagram, shown in Fig. 1.

A review of the classification approaches offered by [17–20] was presented in [21]. Material-based frameworks have been used for grouping additive processes in construction by solid, viscous and power approaches [17]. Similarly, [18] provides process descriptions for additive manufacturing and they relate to manufacturing and in the review framed the reporting of construction methods by material (aggregate, polymer and metal). Also mentioned were the possibilities of 'hybrid' processes and on-site and off site applications. [19] identifies two categories of form filling and additive manufacturing and goes on to subdivide this into binder jetting and extrusion, where extrusion can be horizontal in a layer-wise fashion or vertical. The work presented in [20] differentiates between extrusion and assembly processes. Identifying characteristics of processes in this way helps develop rational argument when reporting research, but falls short of a systematic framework for classification.

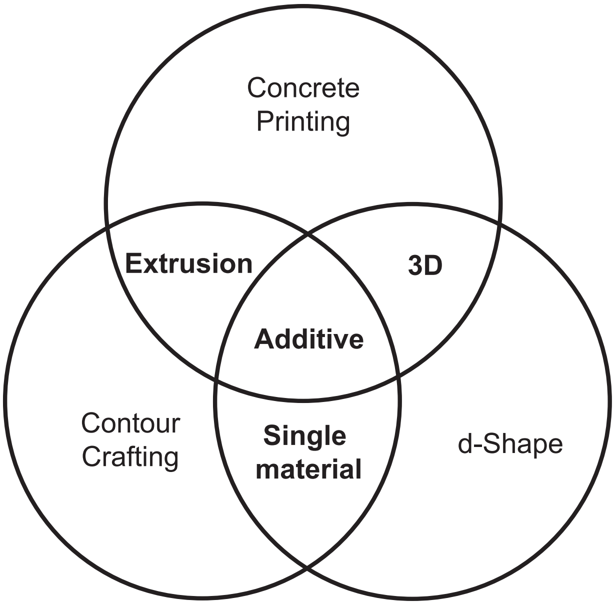

Fig. 1. Diagram from demonstrating the complexity in comparing the similarities and identifying the differences in large-scale additive manufacturing methods in 2012.
Adapted from [6].

Sub-classifications of additive manufacturing processes have also been presented by [22], redrawn in Fig. 2 and [23], redrawn in Fig. 3. The former considered applications for infrastructure construction and identified material extrusion and binder jetting as sub-classes of additive and the latter focused on the selective binding of particles. Fig. 2 follows the [24] terminology for the selective binding of powder: *Binder Jetting: '[is an] additive manufacturing process in which a liquid bonding agent is selectively deposited to join power materials'*. In [23], binder jetting is a subclass of 'Selective Binding Particle-bed 3D Printing' methods.

The term 'binder jetting' used in [24] does not describe the processes of either 'Selective Cement Activation (SCA)' [23] or 'Selective Paste Intrusion (SPI)' [25], which are established approaches used in construction applications. SCA uses water jetted or sprayed onto the particle-bed where it actives the binder (cement) that is premixed into the aggregate in the particle bed. In this application, the water provides the selective solidification operation that enables the manufacture of arbitrary geometries.

Although SPI does selectively place the binding agent onto the particle bed, it does so via relatively slow extrusion process, rather than being jetted and in addition, the term 'powder' in [24], also does not reflect the larger aggregates used in cement-based Additive Manufacturing. Even within manufacturing, some powder-bed and binder methods, jet an activating agent rather than the binder itself and so both the name 'Binder Jetting' and the process definition in [24] is limiting. The term *'Particle-Bed Binding'* would provide a more general term alongside the definition *'[an] additive manufacturing process in which particles of material are selectively joined using a bonding agent'*.

A classification framework of manufacture and assembly processes of building systems using extrusion based processes has been presented in [26]. The system differentiates between on- and off-site fabrication and identifies key parameters for extrusion based systems such as nozzle speed and diameter. The principles of object scale and location were also used by [7] where three application families, or part typologies were classified: components; walls and columns printed in-situ; where permanent formwork is printed and the structural element is cast conventionally. In addition, [26] acknowledge the presence or absence of support during fabrication to enable overhanging features to be created. The geometric consequences of this were also acknowledged in [7], which also included the differentiation in manufacturing orientation: whether the object is manufactured predominantly vertically or horizontally and whether the geometry of a part is predominantly planar or volumetric.

The product of the manufacturing or construction process does inform the technology solution. An observation made in this review was that a further distinction exists in that product geometries manufactured using additive methods can either be made from solid material (i.e. fully dense solid geometry) or a shell (i.e. being hollow), which may be the final object or could subsequently filled with a cast structural material, turning the shell into a solid geometry in an additional step in the manufacturing process.

Within the existing work on DFC, there are classification distinctions between extrusion-based and powder-based additive process,

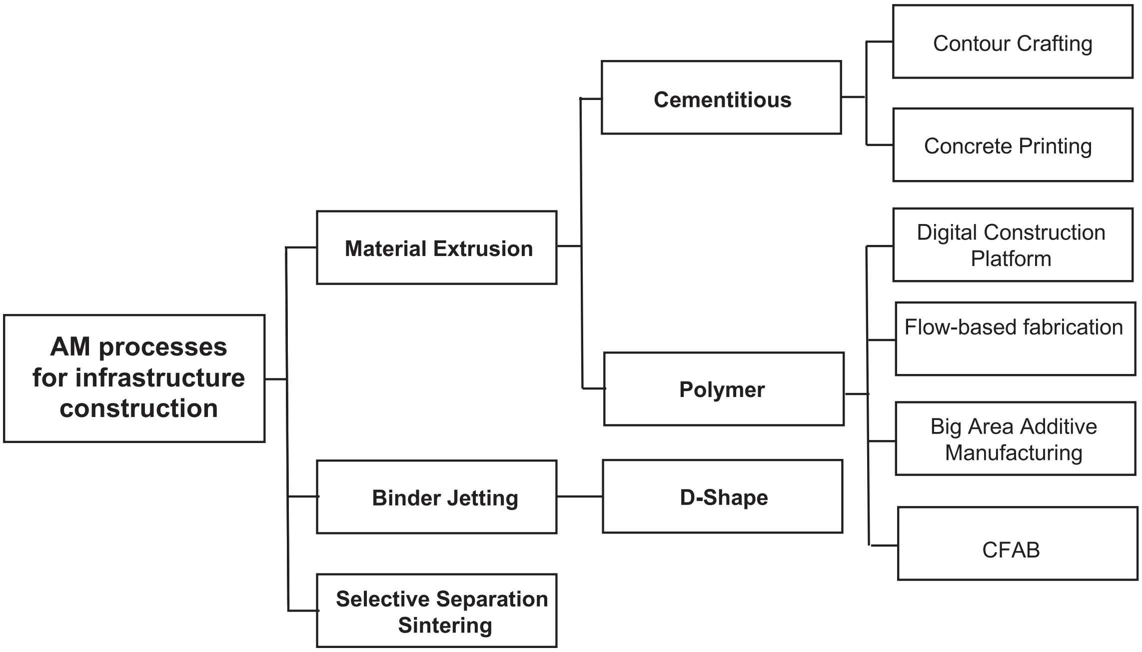

Fig. 2. Process classification.
Adapted from [22].

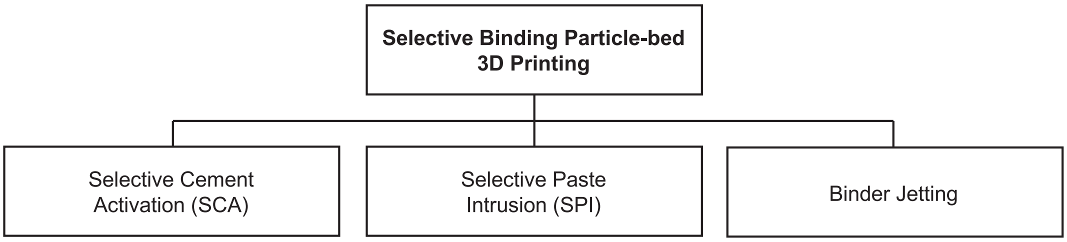

Fig. 3. Process classification of particle-bed methods.
Adapted from [23].

those based on material and on application. In common is the principle binding agent, cement, although how viscosity of the extruded material or the phase change process (solidification/hydration) is controlled may also be a point of distinction [27–31]. However there are no frameworks that encapsulate the broad range of shaping processes observed in contemporary DFC.

Fig. 4 is reproduced from [32] and represents one description of the established framework within traditional manufacturing. It includes *process* and *assembly*, that is reflected in the work of [26]. All assembly operations are relevant to DFC, but of the process operations, the most applicable are shaping processes:

- solidification - setting of a [heated] liquid or semi-fluid;
- particle - where powder is formed into the shape and heated;
- deformation - where a ductile solid is pressed into shape; and,
- material removal - where material is removed from a ductile or brittle solid.

In [24,33], solidification, particle and deformation are all termed ‘formative’ processes, those that shape feedstock (the material supplied to the process) under the influence of force, and material removal is termed a ‘subtractive’ process. Additive Manufacturing sits outside conventional manufacturing processes and have recognised definitions [4]. Seven additive processes are identified in [24,33] and depicted in Fig. 5.

It is difficult, if not impossible, to generate definitive classifications of manufacturing processes, however presenting a rational framework that captures the majority of processes is useful to enable R&D and wider commercial communities to communicate more effectively. There is a need to classify DFC according to process and this should be aligned with existing frameworks such as those practiced in manufacturing and defined in ISO standards.

3. Definitions

It is helpful to differentiate manufacturing and construction by environment, *manufacturing is factory based*, construction happens on-site, placing material in-situ. *Construction* is therefore defined as either the assembly of parts and/or the placement and forming of materials in their final location. A lexicon for DFC is built on the following definitions of commonly used terms:

- *on-site* refers to operations taking place on the construction site that include in-situ assembly and material placement operations;
- *off-site* refers to the fabrication or manufacture of parts of the permanent structure that occur in factory setting;
- *factory* is the manufacturing environment from which products are transported to their final location (the factory may be a located off-site, or in a temporary facility on-site);
- *site* is the construction environment;
- *fabrication* is used here to describe the production of a unitary, or low volume item by largely bespoke combination of processes and

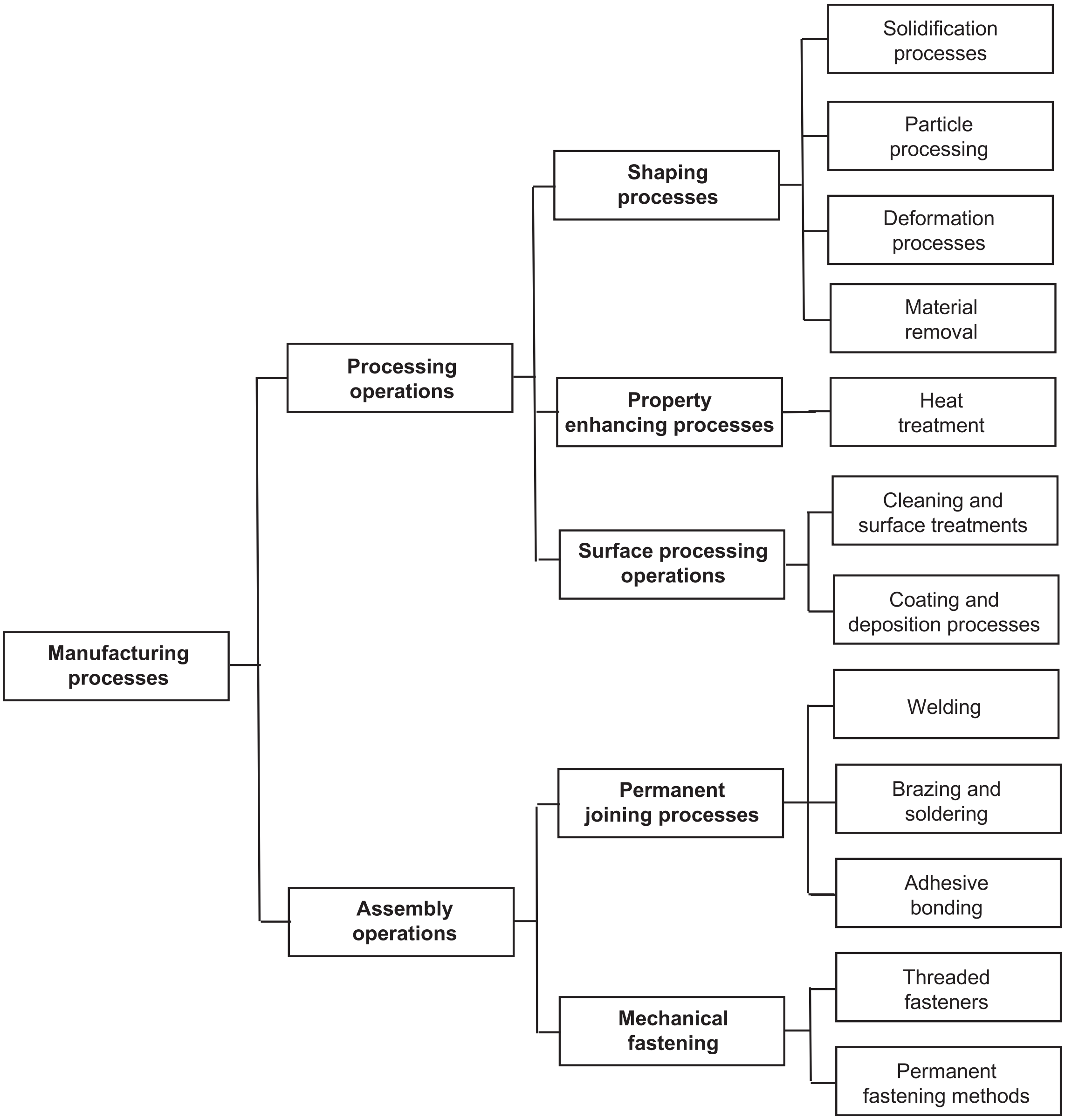

Fig. 4. Traditional (non-additive) manufacturing processes.
Adapted from [32].

operations;

- *manufacturing* is used here to describe the continual production of parts (which may be bespoke or identical) with a specific process and based in a factory for placement or assembly elsewhere;
- *construction* assembly operations, material placement and forming processes that produce part of a permanent installation in-situ, on-site;
- *element* is a part of the building or installation;
- *part* is an item manufactured as either a stand alone item, or as part of an assembly;
- *process* can be either singular when it refers to a shaping or assembly process or can refer to a number of processes when used in context of a *manufacturing process* or *construction process*;
- a DFC *technology* is a generic term for a CNC manufacturing process or construction process; and,
- *sub-process* an indispensable process that occurs while executing the main shaping or assembly process.

The term 'Concrete Printing', and/or '3D Concrete Printing', was originally the name given to the process developed at Loughborough University to differentiate it from Contour Crafting and the d-Shape techniques. It is now a populist term used quite loosely in the DFC domain, in much the same way as '3D Printing' has become a household name for additive manufacturing. However, *Concrete Printing* should refer to those technologies that are additive in nature, i.e. use layer-wise methods to fabricate a three dimensional part, or element where the material is bound together using cementitious binder.

4. Classification principles

Building on the preceding discussion, the classification framework is formed from a number of defining principles that describe (but are not limited too) digital methods for the shaping of cement based products:

- it should encompass the broad spectrum of processes found in DFC, recognising that the 'Digital' in DFC is the enabler of automation and does not necessarily effect the action of process;
- it should maintain the differentiation between on-site, in-situ

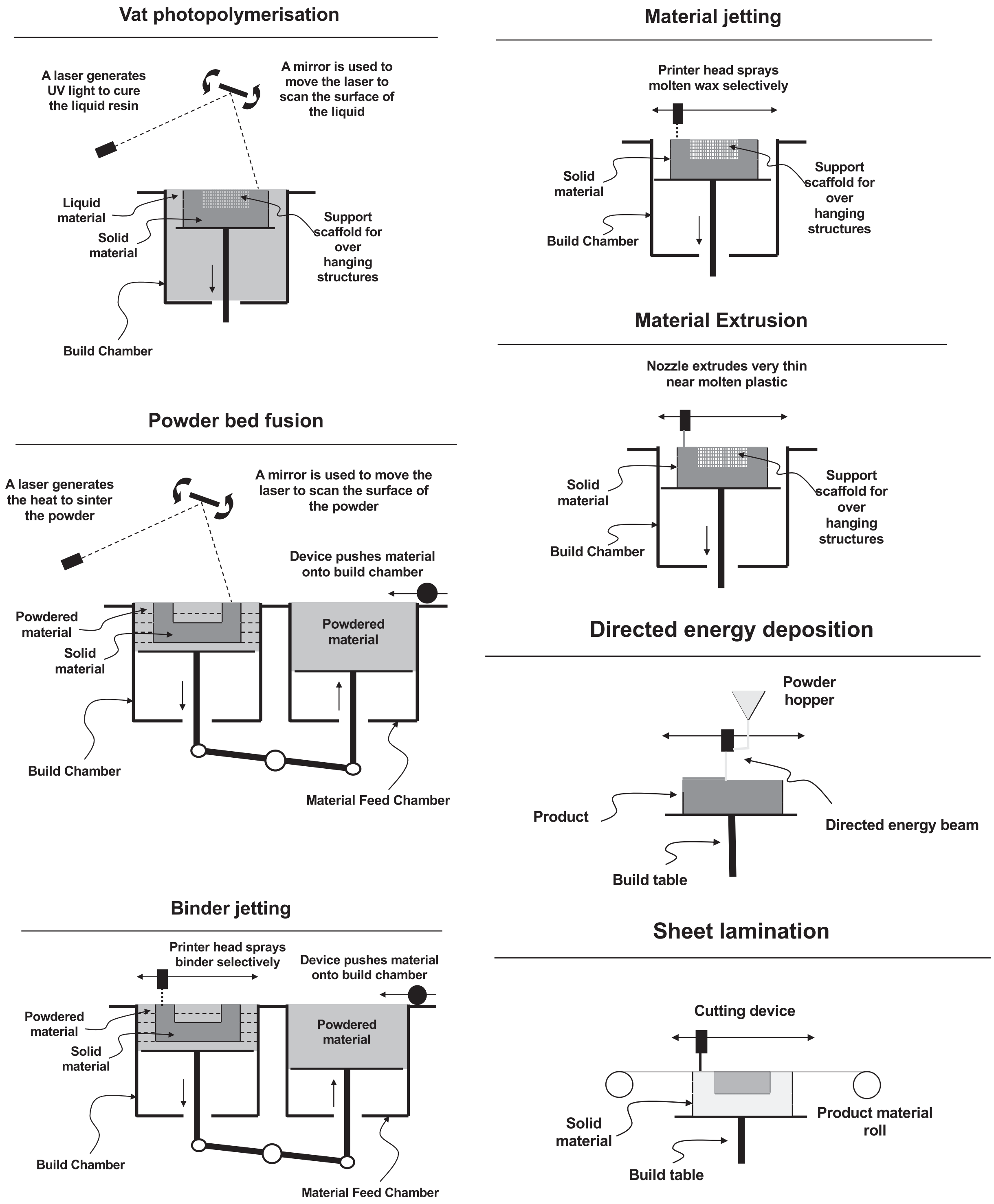

Fig. 5. Additive manufacturing process diagrams redrawn from [34]. Note we adopt the term ‘particle-bed binding’ as the generic process type that (we suggest) should replace the term ‘Binder jetting’.

processes *(construction)* and processes for the production of parts in a factory *(manufacturing)*;

- it should be based on pre-existing definitions and commonly understood frameworks of material forming and assembly processes, such as described by [32] and others; and,
- the framework should seek to build on (or adopt) existing standards such as those that relate to Additive Manufacturing, [24,33].

An important corollary of adopting the principles set forth in [24] is the treatment of ‘sub-processes’ in classification. Where other operations and sub-processes are ‘indispensable’ to the operation of the shaping process, they are not considered to be a ‘step’ in the manufacturing process and so do not affect the classification. Examples in DFC would be the active control of hydration or viscosity [27,30]. It is useful to describe how these processes and sub-processes are executed in relation to each other, which can occur in one of three ways:

- in series;

- simultaneously; or,
- contiguously.

An example of: a series operation would be the casting and subsequent deformation of the flat panel in the Flexible Mould technique [35,36]; a simultaneous operation would be the introduction of the reinforcement cable in an extruded filament as part of an additive process [37,38]; and a contiguous operation would be an alternating interaction, such as placement of support material and build material on each layer during the production of a part using Additive Manufacturing [39].

5. The classification framework and process description

DFC differs from more conventional manufacturing processes because of the need to control the phase change of the material, which is a complex physio-chemical reaction that can be modified from almost instantaneous hardening, to a setting time of hours or days [40,41]. This time dependency is driven by the application and the features that are trying to be reproduced on the part/element (overhangs, or corbeling, for example). In addition, mechanical properties of the final part are not independent of setting time, particularly in layer-based methods. The interlayer bonding is very sensitive to the state of the material [42–44], as is the rate of build in the z direction on the plasticity of the deposited material [45,46]. Both issues are heavily influenced by the geometry of the part/element and the build orientation and so the application of DFC to range of product types and dimensions [7] has resulted in the evolution of many solutions that all use cement as the binding agent, but that are very different at the process level. Given the foregoing, it becomes apparent that DFC technologies need to be described in terms of:

- material(s);
- application environment;
- product; and,
- process boundaries, implementation and sequencing.

These provide the context of the applications as well as the process details and are abbreviated to MAPP: Materials, Application, Product, Process and so the called the *'RILEM MAPP' characteristics for describing DFC technologies*.

5.1. Specifying material(s)

The material used in the manufacturing/construction process should be clearly described according to conventional best practice which include:

- mix design, constituents, grading etc.;
- use of admixtures and hydration;
- rheology control and measurement methods;
- curing;
- shrinkage prevention strategies;
- durability and mechanical properties; and,
- arrangements of blending, mixing, batching and material movement (e.g. pumping/particle-bed layering).

Concretes and cement-based mortars are by definition a composite material, however, in terms of the MAPP definitions, it is treated as a single material, the dry mix being the process feed-stock in wet processes such as extrusion. Cement-based mortars and concretes can be optionally reinforced in a number of ways: with glass fibre, carbon fibre, steel, polypropylene [47–51]; and through methods such as adding short fibers during mixing [52,53]; as discrete placement during the fabrication process, or externally to the part [54,55]. These examples improve the tensile capacity, or the part resilience in conventional ways, but new applications for reinforcement for treating issues relating to layer-wise Additive Manufacturing have also been demonstrated [56,57].

Adding fibers to the batch of cement-based material affects the specification of the mix, and this should be described in the mix design. Where the reinforcement (or other materials) are discretely placed during the process, the process may be considered to be a *multi-material* process, but it will not usually change the classification of the process: the placement operations are considered to be a sub-process.

The term *composite material* would be used where discretely placed reinforcement was used, in that the mechanical properties of the final part/element is through the interaction of the cement-based mix and the reinforcement.

5.2. Specifying application environment

Application environment is important because it defines the control (or lack of) the process is operating under. In specifying environment, the *intended* operating environment should be stated. If this differs from the *actual* environment used to generate results, the actual environment should also be reported in line with good experimental practice. This includes but is not limited to:

- whether it was on- or off-site;
- manufacturing or construction;
- whether part of an assembly, an on-off or in-situ;
- ambient conditions, ideally ambient air temperature and humidity over the process and curing time interval, but also radiant temperature where possible; and,
- material, water and admixture temperatures.

Details of other matters such as curing methods, printing duration and stages of printing over hours/days should also be clearly stated.

5.3. Specifying product

The product whether a part or an element should be clearly defined in terms of its:

- type, what it is, purpose, specification;
- whether it is an 'end-use' part/element or whether it is a mould;
- geometry, shape, density either solid or shell;
- size, overall dimensions;
- build orientation; and,
- fitness for purpose, limits of structural capacity, geometric tolerances, aesthetics, etc.

Images should be used as much as possible to convey the final part and its position when undergoing manufacture.

5.4. Specifying process, boundaries, implementation and sequencing

The *RILEM process classification framework* presented in Fig. 6 may be applied (but not limited) to DFC technologies. The majority of technologies will be readily identifiable, fitting within one classification as long as the specification of the product and process boundaries are clearly defined. Sub-process (those that are indispensable to the operation of the process) should be identified and separated from the principle shaping and assembly processes.

Once identified, these processes and sub-process belonging to a technology should be related in terms of operation, which can be represented pictorially through process diagrams, allowing ready comparison to the operation of other technologies. By way of example, Fig. 7 provides the descriptions of eight well-known DFC processes using the principles set out above. Fig. 8 provides example diagrams for the eight examples listed in Fig. 7. The primary operations are denoted

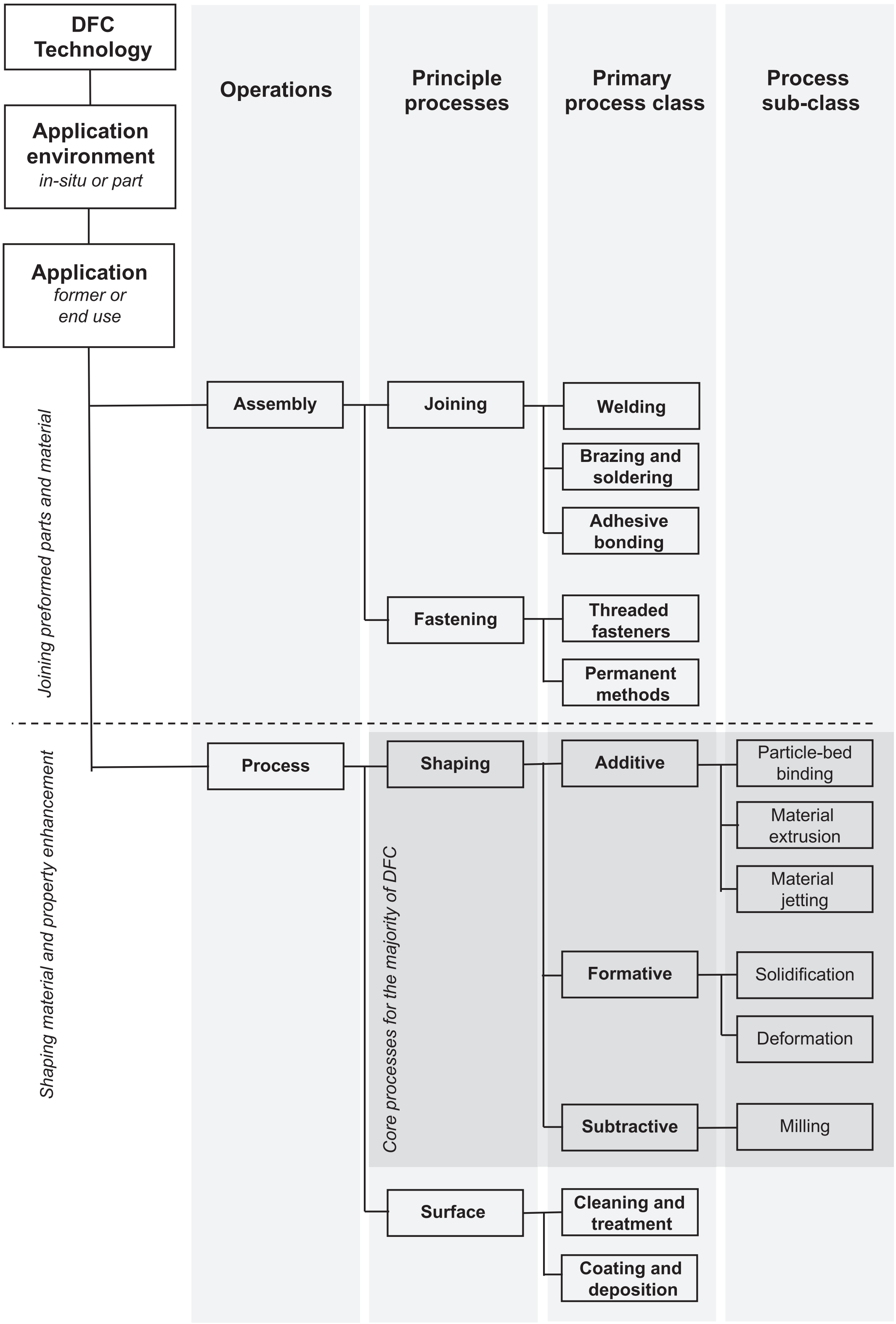

Fig. 6. The RILEM process classification framework for DFC technologies.

with a square and these determine the classification.

These diagrams help identify whether processes and sub-processes operate continually or cyclically and whether they occur in series, contiguously or simultaneously. The diagrams presented in Fig. 8 describe the simplest version of each technology for the purposes of classification, but they can be expanded to depict further detail if required (such as other sub-processes, of which material pumping is a common example). Fig. 8 demonstrates the significant variety in process operation that exists in DFC, even within processes that are in the same sub-class.

ETHZ – Mesh Mould: method for producing the mould for creating wall structures in-situ (construction). The technology is defined by an automated assembly process using welding of discrete bar lengths.

LU – double-curved panels: method for producing panel structures as discrete parts (manufacturing). The technology is defined by the contiguous operation of layer-wise additive manufacture by material extrusion of a build and a temporary support material.

TU/e – bridge parts: method for producing parts from composite material (manufacturing). The technology is defined by the continuous operation of layer-wise additive manufacture by material extrusion, with the simultaneous entrainment of a steel wire within the extrusion.

HuaShang Tengda - wall: method for producing reinforced wall structures in-situ from composite material (construction). The technology uses two contiguous processes: placement of discrete reinforcement and continuous operation of layer-wise additive manufacture by material extrusion.

ETHZ - SDC: method for producing column structures as parts from composite material (manufacturing). The technology is defined by the continuous operation of material extrusion, with an option to simultaneously modify the extrusion cross-section.

d-Shape – 3D forms: method for producing freeform parts (manufacturing). The technology is an additive manufacturing process based om binder jetting (commonly referred to as 'particle-bed') in the field.

ApisCor – formwork: method for producing permanent formwork for casting wall elements in-situ (construction). The technology deploys additive manufacturing using material extrusion to create a formwork. Reinforcement is conventionally placed and casting completes the element.

TU Delft – Flexible Mould: method for producing panel structures as discrete (manufacturing). The technology is defined by three processes in series: mould creation, casting a flat panel and then deformation during curing using a CNC pinbed.

Fig. 7. Descriptions of eight examples of DFC technologies using the RILEM classification framework.

5.5. Use of the term 'Hybrid'

Every effort should be made to clearly rationalise the steps in a manufacturing process or a construction process into singular steps, where process boundaries can be clearly identified. The examples in Figs. 7 and 8 do this and are simple to unambiguously articulate to others. Therefore, specifying the product and the process boundaries is critical. What must be avoided when classifying and describing DFC, is

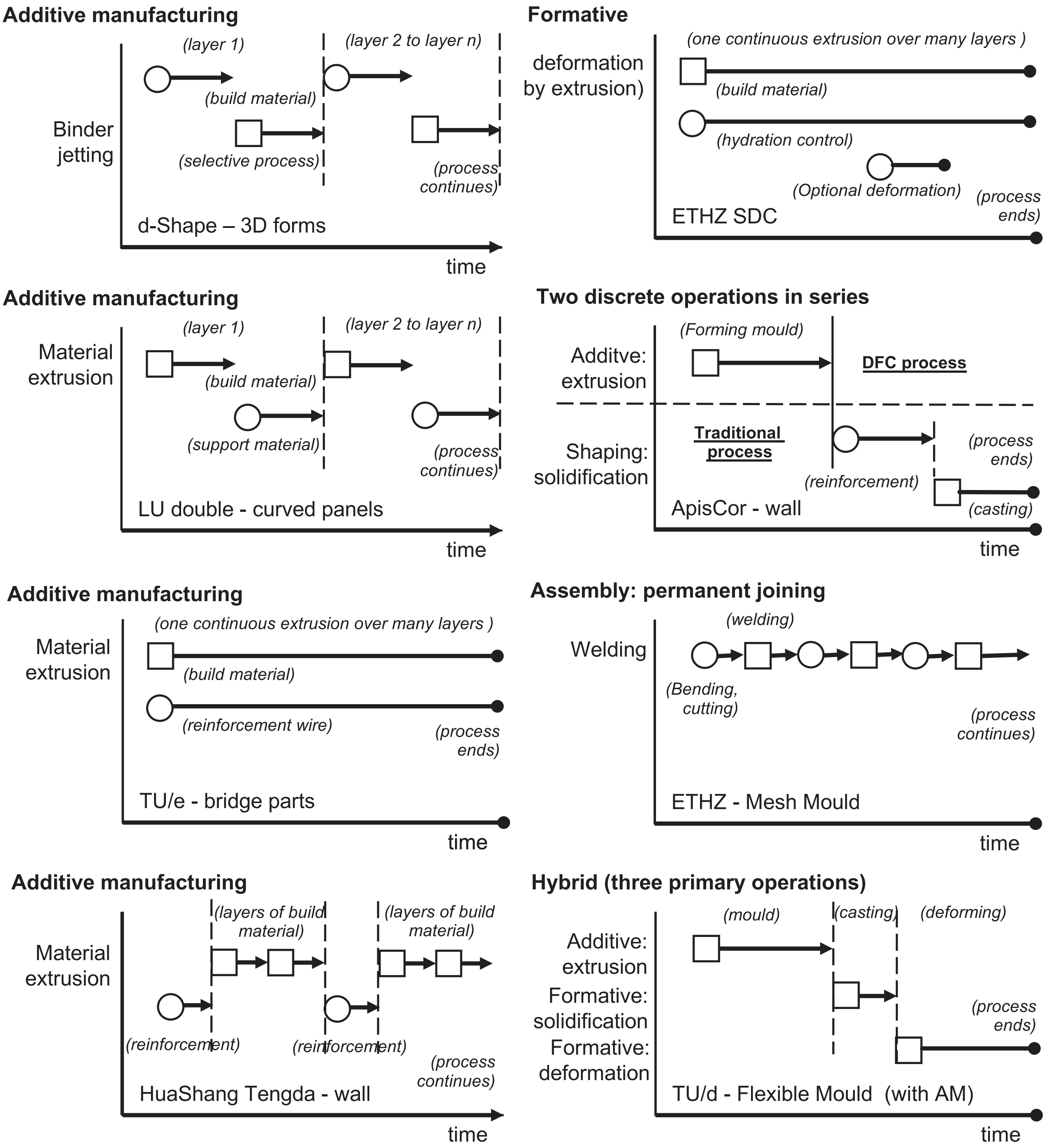

Fig. 8. Process diagrams for the examples described in Fig. 7. The diagrams illustrate the time-wise interaction of primary operations (denoted with a square) and sub-processes (denoted with a circle). These diagrams can be used to graphically explain the differences between DFC technologies.

conflation of a process with the end product which tends to occur around mould making: the product of a DFC technology is typically *either* a mould (for subsequent casting) or the direct fabrication of components with cement-based material.

In DFC there are potential gains in productivity in removing process steps, automating activities sequentially or though some of the novel integration/combination of methods. Occasionally, it becomes difficult, or at least unhelpful to separate a more complex arrangement of processes into individual steps.

A similar problem is evident in manufacturing often when additive and subtractive processes are brought together such as in the Wire Arc Additive Manufacture approaches [58]. The term ‘hybrid’ manufacturing has been used to differentiate these intentional combinations of process for benefit. The term ‘hybrid’ it is not clearly defined, although the following statements offer guidance on when it might be appropriate to use it:

- where more than one primary operation takes place; and,
- the processes are under CNC; and,
- the process act within the boundaries of one ‘machine’.

Some illustrative examples from DFC are:

- Additive manufacturing used to produce a near-net-shape combined with CNC subtractive processes to produce the net-shape might be termed a *hybrid* process: the feed stock (material) is transformed to the net-shaped object in one machine. An example is the CNC trowling applied to Shotcrete 3D-Printing [59,60]. Additive manufacturing used to produce a near-net-shape that is subsequently rendered through hand trowelling to achieve the net-shape is not hybrid, it comprises two steps in the manufacturing processes. In this instance, the classification framework would be applied to the additive process that produces the *near-net-shaped* object.

- Mesh Mould (in its current implementation) uses digitally controlled operations (the 'machine') to manufacture the mould through an assembly process that involves cutting, bending and welding. The casting and trowelling operations are carried out by hand operations. It is not, therefore a hybrid process. In reporting, the product of the Mesh Mould process is the mould and should not be conflated with the end product (the wall). The product of the digitally-controlled 'machine' in this case is the mould. Once established, this is classified as a digitally controlled automated assembly process that utilises welding.
- The Flexible Mould technique for production of curved panels was originally configured to operate through hand placement of a flexible mould edge (e.g. rubber) on a flat pinbed, followed by casting and consequently deformation of the pin bed, which included the edges and the compliant concrete, under CNC. A typically hybrid variant of this process is that where, instead of using rubber mould edges, the mould contours are printed in concrete, using extrusion based Additive Manufacturing, after which the further process is similar. The CNC operations in the former case lies only in the deformation of the material and hence it is classified as a deformation process that acts on a wet/partially cured at concrete element, producing a double-curved part. The latter might be termed a hybrid process because it uses a CNC-based additive manufacturing process in combination with a CNC controlled deformation process in the same machine.

6. Discussion and outlook

This paper presented a classification framework for defining and describing DFC technologies. It is a product of the RILEM TC 276 'Digital fabrication with cement-based materials' and has been developed through international collaboration in open forums between 2016 and 2020. The work addresses the need for developing coherent language and reporting methods to more effectively communicate the processes deployed in DFC in order to: educate those unfamiliar to the field and provide an approach to improve the description of processes in publications.

Critically, the work identified the important of clearly defining the *materials*, *application environment* and the *product* to be made in order to unambiguously define the boundaries of the *process*, allowing identification of then class/sub-class a particular technology belongs too. These were named here the *RILEM MAPP characteristics for describing DFC technologies*.

In addition, the identification of sub-processes that are indispensable to the operation of the process need to be identified and mapped in time and synchronicity to: establish the effect (if any) on classification; and to pictorially communicate the nature of the operation of the process whether this is in *series*, *simultaneously* or *contiguously*.

The work has led to a departure in the current terminology and definition of 'Binder Jetting' in [24] and opt instead to use 'Particle-bed Binding', under which Binder Jetting becomes a sub-class.

The approach here does not term cement-based mortars and concretes as *composite* for the purposed of process classification. A *composite* material is reserved when discreetly placed reinforcement is used resulting in the attendant improvements in mechanical properties. The term *multi-material* is used when there are more than one distinct material being used.

To move DFC technology towards wider adoption in industry, the need for process certification and standards will be required and it is hoped that the principles and lexicon presented in this paper will provide the international community with a sound basis on which to start.

CRediT authorship contribution statement

R.A. Buswell: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.**W.R. Leal da Silva:**Conceptualization, Methodology, Writing - review & editing.**F.P. Bos:**Conceptualization, Methodology, Writing - review & editing.**R. Schipper:**Conceptualization, Methodology, Writing - review & editing.**D. Lowke:**Conceptualization, Methodology, Writing - review & editing.**N. Hack:**Conceptualization, Methodology, Writing - review & editing.**H. Kloft:**Conceptualization, Methodology, Writing - review & editing.**V. Mechtcherine:**Conceptualization, Methodology, Writing - review & editing.**T. Wangler:**Conceptualization, Methodology, Writing - review & editing.**N. Roussel:**Conceptualization, Methodology, Writing - review & editing.

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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