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Real Direct Digital Manufacturing Transforms Additive Manufacturing

Abstract – The recent rapid growth of additive manufacturing (AM) has pushed an essentially prototyping technology into the realm of demanding component production for end users. The challenges brought by the latest advancement are systematically investigated to sustain and enhance the strong growth momentum of AM. Digital manufacturing (DM) and direct digital manufacturing (DDM) are identified respectively as the two major manufacturing paradigms to include all the significant advancements in modern manufacturing so far. The underlying driver to the two step changes is understood as their thrust by the revolutionary manufacturability, which can be measured in system flexibility, product complexity, and process robustness. Such a metric comprehends all characteristic performance required for high product value, high product quality, short lead-time, and low cost. By digitizing conventional analog manufacturing, DM has achieved a radical improvement in all three criteria in the manufacturability metric. Virtual manufacturing (VM) is marked as a special scenario of DM with full digitization to support simulation and analysis via virtual models, images, and animations. The essence of AM is found to be DDM since the system directness overcomes many barriers to the manufacturing conversion from a virtual model to a real product. As a differential to DM, DDM has achieved another radical improvement in two of the three criteria, i.e., system flexibility and product complexity, by deriving the direct manufacturing convertibility from the virtual printing setup. The near virtual and highly digital manufacturing system encounters much lower impedance to a direct model-to-product conversion. As for DDM, system flexibility and product complexity increase while process robustness declines. The transition from printing as a virtual technology to DDM as a real manufacturing one introduces certain virtual attributes, which entail process redundancy, open exposure, and unrepeatability. Hence, the lower process robustness of DDM is attributed to the inherited virtuality from printing. Besides the two major transformations of DM and DDM, the third transformation by system realization is proposed and investigated to overcome the low process robustness of DDM. Real direct digital manufacturing (RDDM) makes a realization to DDM by diminishing its virtual attributes in the energy flow, information flow, and material flow of the manufacturing system to compensate the deficit in process robustness. As an example of RDDM, 3D building is devised and investigated accordingly to replace the specific printing attributes in 3D printing by turning an open and redundant printing system into a compact and efficient building system. The enhanced system reality by 3D building results in an increase in not only process robustness but also product complexity and system flexibility. Besides 3D building, other RDDM can be devised to make other realizations to other DDM scenarios.

1. Introduction

The opportunities and challenges of additive manufacturing (AM) keep emerging as academia and industry reveal more and more about the essence of such a unique layer-upon-layer process. Driven by considerable investment and demand, the pre-pandemic average annual growth of worldwide AM industry attains 26.7% over the past 30 years and 23.3 over the past 4 recorded years [1]. Growth sustainability at such high level requires further fundamental transformation and breakthrough understanding of the distinct manufacturing configuration. Inspired by conventional desktop printing, 3D printing (3DP) enables a direct conversion from a virtual model to its physical product by replicating the complex design information in real form and material. The material flow and energy flow of different AM modalities [2] follow a typical printing process to different extent. Material addition alone does not promise the same direct convertibility in replicating the high feature resolution and intricacy. Since some modalities deviate more from printing than others, their model-to-product conversion are less direct and subjected more to tooling and material constraints. Apparently, material addition is not the essence of AM, which demands more profound research. Simulating paper application in a printer, powder bed fusion (PBF) and binder jet actually recoat the entire top surface area with a blank layer of powder at the beginning of each printing cycle. VAT photopolymerization shifts the part down to create a top blank resin layer instead of powder layer. The transplanted printing setup, though enabling the necessary direct conversion, can compromise the integrity and efficiency of usual manufacturing system. A simple replacement of other established manufacturing technologies with 3DP or AM does not automatically result in the well-known benefits but often caveat shortcomings. As for 3DP, the open extensive setup with numerous diverse process parameters make process control and compensation more difficult than any other precedented manufacturing systems. Further AM expansion will depend on significant enhancements in system manufacturability and new configurations of highly valuable products only AM can make. The key to both opportunities is a systematic comprehension of the special printing configuration and characteristics. First, the unique thrust to the extraordinary successes so far should be identified better and exploited more including the root of AM in digital manufacturing as well as desktop printing. Then, the printing setup can be transformed accordingly for a step change in manufacturability while maintaining and enhancing the original thrust of 3DP. Such a paradigm shift can trigger another wave of disruptive innovations across a new R&D landscape.

In the ASTM standard [2], AM is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” to distinguish AM from subtractive manufacturing. Although the term of AM distinguishes additive manufacturing from subtractive manufacturing, casting and injection molding among other conventional formative technologies are also additive in nature. The ISO/ASTM 52900 standard [3] further distinguishes AM from not only subtractive manufacturing but also formative manufacturing. The perspective of material processing leads to a multi-layer deposition technology, which decreases productivity and introduces stresses in material. However, the material processing definition does not capture the essence of AM, which can only be acknowledged from a broad perspective of manufacturing system. The present research will explore existing alternative definitions [4] including rapid prototyping, additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication, solid freeform fabrication, and direct digital manufacturing among others in order to capture its true essence and major thrust, driving all the AM applications and developments. Direct digital manufacturing (DDM) [5] is found to be the closest to the purpose of comprehensive characterization although necessary elaboration will be developed to enrich the preliminary concept. The current research will address the role of digitization and directness respectively.

- Define and characterize digital manufacturing (DM) as opposed to analog manufacturing.
- Define and characterize DDM as a differential advancement over DM to relieve indirect manufacturing limited by the conventional constraints in tooling, machine, and processes.
- Propose and characterize real DDM (RDDM) as a further differential advancement over DDM to counter the negative virtual effects on material quality and process robustness. Real manufacturing (RM) is defined as opposed to virtual manufacturing (VM).

As a transformative paradigm, RDDM overcomes many virtual attributes DDM inherits from the conventional printing, a technology based on desktop engineering. The virtual attributes do not appropriately serve the purpose of physical manufacturing and its process robustness under a real manufacturing environment. The transition from DDM to RDDM is expected to bring about the unprecedented overall manufacturability including system flexibility, product complexity, and process robustness. DDM has already been the most state-of-the-art technology; RDDM goes another significant step forward.

All derived from 3DP, AM with 8 modalities [2] represents the latest abrupt manufacturing advancement by realizing direct model-to-product conversion, which has brought about the best system flexibility of all the manufacturing technologies developed and applied so far. In the first wave of AM business expansion, this advancement by DDM has led to the extensive adoption of rapid prototyping (RP) [6] in producing pilot components, trial tooling, customer medical parts, and extra-large parts, etc. The second wave of AM business expansion, which has turned out to be greater than the first one, took the advantage of the unmatched DDM capability in product complexity. In GE and other aerospace companies, direct metal laser melting (DMLM) has enabled the consolidation of many hundreds of parts into one extremely complex integral component to increase system performance and to cut manufacturing cost significantly at the same time. As a bonus benefit, the collapse of manufacturing processes and entire supply chain significantly reduces the cost in management, logistics, and delinquency. For the first time, prohibitively complex devices of highly engineered structures and materials can be produced and finally liberated from almost all conventional manufacturing constraints. The conventional indirect and subject manufacturing had frustrated many dream designs until DMLM overcame the constraints. Most of the time, DMLM must take on serial production after necessary prototyping and technology substantiation because no other advanced technologies are cable of producing such complex components or devices even with complex tooling and machines. In addition, other technologies do not get the benefit of low manufacturing cost. To DDM\DMLM, serial production at considerable volume is a new challenge. Process uncertainty and unrepeatability emerges [7, 8, and 9] as quality problem in prototype manufacturing and especially in serial production. RP on an ad hoc and trial basis does not require high process robustness since the relatively low cost of product defects can be easily managed, given the number of few required part counts. For volume production, the higher defect rate will demand frequent and complete inspection including destructive inspection in technology substantiation as well as regular manufacturing operation. Inspection and qualification must be much more extensive to cover not only processed surfaces but also all built material. The high system sensitivity, numerous critical parameters, and thorough processing extent can all contribute to the reduction of process robustness. Reactive measures are proposed and researched to encounter the extensive problems exhaustively including the powerful detection by high-speed X-ray [10, 11] and thermographic imaging [12], operando characterization and modeling by AI and supercomputer, real-time process control including laser beam and material flow etc. In addition to common reactive measures, the current research adopts fundamental change to target the root causes and structural issues in 3DP. The efficient strategy is problem minimization or even elimination before any solution to cut the solution extent and cost. In other words, the intrinsic process robustness is improved before a powerful process control is developed and implemented.

It is of essential interest to identify what drives all modern manufacturing advancements. The monumental success of Henry Ford's moving assembly line, invented in 1913, has basically solved the productivity problem by distributed manufacturing. Productivity is no longer a technological challenge, but only an economic one sometimes. Demands for high system flexibility have driven the development of flexible manufacturing system (FMS) and reconfigurable manufacturing system (RMS) [13]. The system flexibility allows manufacturing a variety of products on the same system and adapting product changes to meet unpredictable market change. Manufacturability in making complex products of highly engineered geometry, structure, and material is always in demand with ever-increasing needs. As a metric for product performance, product complexity is limited by the system capability of machine, tooling, processes, and their configuration. Process robustness is the key to high product quality with minimal variability and defects, which are critical to manufacturing competitiveness. System flexibility, product complexity, and process robustness constitute a complete manufacturability metric to evaluate the performance of any prevalent system and technology advancement. System flexibility (SF) is referred to as the ability of manufacturing system to rapidly adapt variable product type, size, design, and material. SF can be evaluated by 3 factors:

$$SF = (Programmability \times Reconfigurability)/(Tooling\ Restriction) \qquad (1)$$

Product complexity (PC) can be measured by the manufacturable density and intricacy of structural or geometrical features. Intricate features include hardly accessible or blind cavities, which can be interconnected. PC is evaluated by 3 factors:

$$PC = (Feature\ resolution) \times (Feature\ density) \times (Feature\ Intricacy) \qquad (2)$$

Process robustness (PR) is referred to as the ability to tolerate variability of raw materials, process parameters, equipment/machine, environmental conditions, and human factors. PR is evaluated by 3 factors:

$$PR = [(System\ sensitivity) \times (Parameter\ counts) \times (Process\ extent)]^{-1} \quad (3)$$

It is noted that SF, PC, and PR are mutually competing to one another in a manufacturing system. Figure 1 shows the competing effects in a 3-pole radar chart. Increase in SF can occur at the expense of PC and/or PR since the added flexibility to changes can be offset by additional system tolerance to process variation and/or corresponding sacrifice in product complexity. By the same token, higher PC can be offset by lower SF and/or lower PR, and higher PR can be offset by lower SF and/or lower PC. However, a disruptive manufacturing advancement, such as DM and DDM, can break the mutually competing correlation to achieve a fundamental advancement simultaneously on at least 2 or all 3 criteria.

It is not surprising that low PR emerges as an expense of high SF and PC in DDM. DDM has made a step change in two of three criteria, i.e., SF and PC, to make it a revolutionary advancement. Demand for improvement in PR, the last criterion, is mounting as to make another business expansion. As the next fundamental change, RDDM will be manifested to attain even better PR, SF, and PC than DDM.

2. <u>The Development of Digital Manufacturing</u>

Since the essence of AM is just DDM, we use DDM from now on to denote AM. As the latest manufacturability leap, DDM originated from DM. According to academic and industrial definitions [14, 15], DM is an established broad foundation for all modern manufacturing advancements, requiring such digital resources as computer, database, as well as network. NC/CNC machining, digital forming, automatic assembly, and virtual manufacturing (VM) are all typical scenario under the broad umbrella of DM. DDM realizes a differential development from DM by eliminating the tenacious manufacturing constraints to directly convert a virtual model to its physical replica. The deficient manufacturability in DM creates the demand for DDM; however, the deficient manufacturability in analog manufacturing creates the demand for DM first. Hence, it is necessary to understand the manufacturability of DM first.

2.1. Evolution and development of DM

Manufacturing digitization started from numerically controlled contour machining [16] in the absence of computer when computer had not become prevalent yet. In contemporary NC and CNC machining, the continuous 3D trajectory of tool motion is divided into fine segments and then interpolated in G-code programming. Following a part program, the cutter motion can generate the necessary part contour without a hard cam or manual machine maneuvers as done in the traditional analog machining. The analog tool motion follows a solid cam or masterpiece, which is difficult to make and worn quickly in use. The cam, as a hard information carrier, could only provide simple and unsustainable forms. Machine control by operator maneuver and scale measurement by naked eyes are inaccurate and irregular. Dependence on operator skill and machine maintenance can entail large product variability. In NC/CNC, the hard information carrier is turned into a soft and sustainable one, i.e., program data stored on a tape, disk, or memory chip. Information flow is totally digitized and automated via digital scale, digital controller, and digital driver etc. Digital information is programmable to significantly facilitate the SF for efficient product change and update by saving difficult drafting and drawing on blueprints and hardcopies. Digital design model can be much more complex and sophisticated than what paper drawings can contain to drastically increase the capacity of PC. In addition, digital information flow is immune to analog disturbances and interferences for much higher PR. Scoring significantly higher across the board, CNC as the first DM success increases SF, PC, as well as PR concurrently and significantly in contrast to analog machining to set a precedence of fundamental change. Besides machining, other manufacturing technologies such as forming can also digitized to various extent. Table 1 summarizes the impact of digital advantages to the 3 metrics for system manufacturability. For example, the higher design and modeling capacity can provide for higher SF and PC as the digital software system enables more complex product and/or more product changes. For another example, higher information integrity promises higher resistance against noise and interference to provide for higher PR. As shown in table 3, the total effect of these digital advantages reaches triple positive for all three metrics.

CNC also lays the foundation for flexible manufacturing system (FMS) [17] and later reconfigurable manufacturing system (RMS) [13]. FMS can make a variety of different products without much need for additional programming while RMS adds more flexibility in system structure and scale to adapt to much greater changes in product design and even production layout. Apparently, FMS and RMS increase SF far beyond what mere CNC can achieve. Given FMS and RMS, significant product change does not necessarily require much system reprogramming or restructuring but just parameter changes to accelerate the turnaround from concept to market. This thrust to increase SF also drives RP further, resulting in even greater SF with much less extensive equipment resources.

As CAD rapidly advances with the exponentially increased computing power, much more complex components and assemblies can be designed in much shorter cycle time than manual drafting on blueprints. The almost unlimited memory capacity can accommodate unprecedented PC. CAM is developed to streamline the conversion from a complex CAD model to its NC programs for machine. System robustness significantly increases since the stored profile information in a digital media never wears despite the numerous numbers of application and edition. To guarantee the PR, CAM conversion shields the data from many possible human errors in data processing.

Based on computer-controlled motor drivers, optical digital scales, and computer feedback system, a fully digital machining system can deliver much higher precision and suffer no sensitivity to numerous analog interferences in the machining system. Some execution mechanisms in manufacturing system are not fully digital due to the limit in the special electrical and mechanical designs. Perfect digitization is ideal but usually impossible when it comes down to particular execution mechanisms.

2.2. Manufacturability dependence on digitization strength

As for subtractive manufacturing or just machining, system digitization has already been rather thorough from solid model generation to tool motion control. As for formative manufacturing, the system digitization is limited to tool manufacturing while the forming process is still mostly analog as far as the material flow is concerned. For instance, the die or mold for casting, forging, or injection molding can be all machined by CNC following the program data generated from a CAD model by CAM conversion. However, a forming tool, once made, does not allow quick design change until the tool is remade.

The tool as the hard information carrier does not provide the necessary SF in a formative manufacturing system such as casting, forging, or molding. Though the tool form is digitally made, the analog forming process is still subjected to the sensitivity to environmental interferences, unpredictable tool wear, and irregular material/energy distribution. This partial digitization prohibits the full benefits of DM. Unlike conventional formative manufacturing, 3D double-sided incremental forming does not use a contoured stamping die but just generic tools without the final part form [18]. CNC drives the 3D motion of the top and bottom tools to compress a 3D sheet form from planar sheet metal stock. Hence, it is a digitized manufacturing system. CNC EDM die sinking is another manufacturing system that uses a formed tool or electrode to generate a mirrored shape on workpiece by subtractive sparking erosion. Nevertheless, the contoured electrode can be digitized in 3D space [19] for the complete due benefits of digital manufacturing including significant manufacturability improvements in contrast to a monolithic electrode machined by CNC but subjected to analog process effects, such as nonuniform electrode wear.

Figure 2 demonstrates the information flow and its digitization strength in a manufacturing system. Although the digitization has already spread in all modern manufacturing systems, digitization degree varies from the most digitized systems of CNC machining to the least digitized systems of formative manufacturing. In a manufacturing system, the information flow starts from definition generation, to information conversion, to information flow in equipment, and to form creation process. The information processes include but not limited to design model/drawing, machine instruction/programming, machine motion/process control, and form generation. It is difficult to digitize every process in a large manufacturing system. Key part of some systems remains analog. For instance, most formative manufacturing systems adopt an analog tool to form product though the tool is most likely digitally made. The key for complete digitization is to make the entire information flow digitizable and thus manageable especially when the information flow is carried out through a substantial material flow.

Table 2 rates the digitization strength of various manufacturing technologies with at least some degree of digitization. No pure analog technology is included in the table. In other words, the digitization strength > 0. From 1 (the lowest) to 3 (the highest), the rating for digitization strength, though close to qualitative, can give affirmative results. The overall strength is calculated per the equation below:

$$Digitization\ Strength = \sqrt[4]{Difinition\ DGTZ \times Equipment\ DGTZ \times Coversion\ DGTZ \times Process\ DGTZ} \quad (4)$$

where DGTZ stands for digitization. CAD prevalence has made almost all geometric definition digital since paper drawing became obsolete for essential quality control. The strength of definition digitization is all high for all contemporary manufacturing technologies as shown in table 2. The digitization of manufacturing equipment depends on the digitization of process measurement, motion control, and power control among other necessary equipment functions. For example, CNC machines are more digitized nowadays than a usual casting foundry as such and other formative manufacturing systems. A digitized machine is more accurate, robust, and reliable than an analog machine. Information conversion from design definitions to executable programs needs dedicated software such as various CAM products; otherwise, tedious conversion by operator can be a source of human errors. The standardization by G code and PLC has enabled the CAM prevalence for CNC machining. General conversion software is less available and difficult to develop for formative systems, such as casting and forging, which are usually special and dedicated to certain product. Process digitization makes the greatest difference in the overall digitization strength because most formative manufacturing processes including die forging, die casting, sheet stamping, and injection molding are analog in nature. Their tools including all the dies and molds can be generated by CNC machining, a fully digitized process, but formative processes themselves can hardly be digitized until the invention of 3DP. 3DP disrupts the continuous material flow of casting or molding by material layering to certain thickness, which has finally digitized the formative processes. Table 2 basically gives a two-tier categorization, one for high digitization strength and the other for low digitization strength. The manufacturing systems of high digitization strength include CNC machining, 3D double-sided incremental forming, and 3DP. The rest pertains to the category of low digitization strength. This rating strategy can be applied to determine the appropriate manufacturing technology of the best manufacturability for certain product need. The strength scales can be refined for discernable resolution.

For any DM system, the higher the digitization strength, the higher the system manufacturability measured by the 3 criteria, i.e., *SF*, *PC*, and *PR*. By a 3-pole radar chart, figure 3 illustrates the impact of digitization strength to system manufacturability. Constituted as a fundamental improvement, the manufacturing digitization in DM enables significant and simultaneous enhancements in all three criteria. The digitization strength is rated from 1 to 3 with 3 being the highest. Unlike common reactive improvements, the fundamental change by DM does not have to attain a significant improvement in one of the three metrics at the expense of other two metrics. DM introduces parametric modeling, model complexity, and interference immunity to increase SF, PC, and PR both simultaneously and significantly. The qualitative improvements shown in figure 4 are illustrated to be relative to digitization strength, which can be approximately quantified by following table 2. The relative manufacturability of different manufacturing systems can then be estimated and compared when it is necessary to evaluate the options or to invent new technologies. As shown, NC/CNC machining, 3D double-sided incremental forming, and 3DP have the highest score of 3 in digitization strength.

2.3. DM characterization and distinction among DM, RM, and VM

Figure 4 categorizes various manufacturing systems according to digitization strength and material flow direction. Below, algebra of sets is applied to characterize the definitions and relations to one and other accurately.

$$DM = VM \cup (RM \setminus (Analog\ Mfg.)) \quad (5)$$
$$RM = (Analog\ Mfg.) \cup (DM \setminus VM) \quad (6)$$
$$RM = VM^C = \{SM, FM, AML\} \quad (7)$$
$$VM \cap RM \neq \emptyset \quad (8)$$

DM evolves into the realm of virtual manufacturing (VM) as digitization strength increases. Operating entirely within computer systems, cyberspace, and desktop devices, VM [15] attains full digitization strength since it occurs only on computer screen or other visualization media basically. VM is independent from any analog mechanisms, chemistry, and/or physics, in which real manufacturing (RM) must involve while running concrete material processing and operation. VM appears to be a fast-developing toolbox including virtual reality, AI, AR, digital twin, and IIoT, etc. as the power of computing, networking, and cyber space rapidly increases. According to (5), DM includes VM and RM except analog Mfg. According to (6), RM includes analog mfg. DM except VM. Despite the categorization intricacy, all the systems and technologies in the domain of RM and the intersection of VM and RM are still evaluated per the 3 introduced metrics, i.e., SF, PC, and PR. It is noted that pure VM or $VM \setminus (VM \cap RM)$ has almost infinite manufacturability in SF, PC, and PR because of the practically infinite computing power. Apparently, pure VM does not produce any physical product but only a virtual one via virtual media, such as screen display or paper drawings.

The infinite but virtual manufacturability of VM would be attractive if it could be materialized in a real manufacturing environment rather than confined in a virtual computing system. We should remember that the infinite manufacturability is only applicable in producing virtual objects such as design models, drawings, images, and process animations, etc. It is very attempted to turn one of these virtual processes into a real one to make physical object. 3DP actually made a breakthrough by following the transformation strategy. 2D printing is a virtual process to produce drawings, a virtual representation of physical part. 3DP adopts the similar printing process but stacks up profiled layers to make functional and real products instead of the virtual products in the form of paper drawings or model displays on screen. In this sense, the distinction between the virtual process and real process nearly disappears since they all prints as such. Hence, overlap between VM and RM appears as shown in figure 4 and given in equation 8.

In general, VM is a computer-based methodology for defining, simulating, and visualizing the manufacturing process early in the design stage, when some, if not all, manufacturing-related issues can be detected and addressed. Virtual prototyping saves cost and time but cannot substitute real prototyping. At the end, the manufacturing technology and product must be substantiated in a real manufacturing setting. However, VM overlaps RM. The ever-expanding interaction between VM and RM makes manufacturing system increasingly powerful, but totally blurs the boundary between the two scenarios. For instance, AR [20] is basically in the RM scenario but greatly enhanced by online simulations among other VM technologies. On the other hand, AI among other methods in VM domain cannot work without real data in RM domain since AI needs to be trained by the real data.

As the distinction between VM and RM blurs, process risk remains as one last criterion to distinguish between the two technology realms. No pure VM can entail any physical product failure or direct damage as a consequence. A virtual process alone, though it can stimulate violent physical activities, cannot result in any hardware damage in the computers or other involved digital media. One can run numerous simulations and virtual trials even under extremely aggressive settings while the computer system is always unscathed. On the other hand, the risk of RM always exists including the negative impact to manufacturing system and product. The consequence can be as direct as equipment failure or product damage due to overloading. As indirect consequence, defected parts can incur underperforming product and shorten product life. Uncertainty occurs when virtual technologies are applied in a RM system. AM is derived from a virtual technology, i.e., 2D printing, in making real parts rather than just printing drawings on paper or screen. Hence, AM faces all the physical risks as a technology of RM though it depends on many virtual attributes for printing. Substantiating these unreal attributes under a real setting will be challenging.

3. Direct Digital Manufacturing as a differentiation to Digital Manufacturing

Although the forming tools are digitally made, the analog material forming processes in formative DM indicate incomplete digitization. In this context of digitization development, AM turns out to be the ultimate digitization of the analog forming processes. As shown in figure 5, the injection casting process is analog though the casting dies can be made digitally by CNC machining. Selective laser melting in a powder bed does nothing but digitizes the die casting process. Laser PBF can also digitize other formative processes, such as forging and injection molding. This digitization breakthrough by AM has hardly been recognized and understood until now. Following the perspective of material processing, AM is defined as opposed to subtractive manufacturing (SM) [2] and formative manufacturing [3]. The layer-upon-layer digital additive process from 3D CAD data illustrates the ultimate digitization of conventional formative DM. However, the perspective of material processing does not clearly recognize direct digital manufacturing (DDM) as the system essence of AM. What drives the disruptive AM advancements is the system directness in converting a digital model to a physical device, which can be complex and highly engineered in structures and materials. AM is necessary but not sufficient condition for DDM. Not all AM modalities [2] have the equal power to convert a complex model to its physical replica with little deviation. For instance, laser PBF can reproduce a much more complex 3D model to its physical form than material jetting and DED, which require post machining to attain the complexity and details. It will help AM development to reveal and characterize the manufacturing power of direct conversion.

3.1. DDM distills the essence of AM

The definition of AM is based on the material processing methodology but not from the broad perspective of manufacturing system. As far as DDM is concerned, the actual power of AM is absent in literal sense. DDM constitutes a direct conversion from a CAD model including material and tolerance specifications to an exact physical replica regardless of model and specification complexity. It alludes to a total liberation of product design from any manufacturing constraints. DDM is referred to as a digital manufacturing system, in which certain material flow and energy flow digitally build a physical part directly from its model definition and without tool and material obstructions to the information flow. The current term of DDM [4,5] is elaborated and redefined to capture the essence of AM. As shown in figure 5, laser PBF can effectively be a digitization of such a formative process as die casting. As shown in figure 6, 3DP is inspired by conventional printing but extended vertically by layer-up-layer stacking. The developed technological intricacy results in DDM, a direct conversion from 2D drawings to 3D part without the common manufacturing challenges including tool inaccessibility in an interior vacuity, resolution limit of tool tip or dip radius, and difficult materials for machining or forming.

Qualified as DM but not enough as DDM, CNC machining cannot create an undercut out of sight line because the cutter does not have the necessary accessibility beyond preexisting material. Switching from material subtraction to material addition eliminates the material obstruction and the need for cutting tool. Material addition facilitates the fabrication of hidden cavities shown in as long as cavity walls stand almost vertically. Material addition does not necessarily provide the manufacturability for horizontal overhangs unless support material is available below. For instance, DED or other spraying modalities cannot form an enclosed vacuity of accurate definition, although a spraying process can produce arbitrary voids. Die casting in a formative manufacturing system cannot create an almost enclosed cavity either because a casting die cannot have a dangling part in the middle. The other constraint to the direct conversion is in manufacturing resolution while a CAD model can attain virtually infinite resolution. In practice, the minimal radius of tool tip and dip basically sets the limit of resolution. Unlike a focused laser beam or much less a computer modeled micro feature, a tool tip and dip cannot be made so small as to compromise its physical stability. For most AM modalities, the minimal amount and best precision of material addition limit the manufacturing resolution. Easily focused to a spot of just a few tens of micrometers, laser beam can create an extremely small feature radius for very high manufacturing resolution to avoid the considerable stress and wear on tool tips or dips in machining and forming. Figure 6 illustrates the potential feature complexity and density achievable by laser PBF among other 3DP options. 3DP includes binder jetting and various PBF technologies, which all requires powder recoating for each build cycle or layer. It should be clear by now that AM is a necessary but not sufficient condition of DDM. Perfect DDM is an ideal scenario that only laser PBF or 3DP in general can approach but still cannot completely attain.

From figure 4 and 7, the equations below hold.

$$DM = VM \cup DDM \cup (RM \setminus (Analog\ Mfg.)) \quad (9)$$

$$DDM = RM \cap VM \quad (10)$$

Equation (10) indicates DDM is derived from a crossing methodology from VM to RM or vice versa. Just like many contemporary imaging technologies, conventional printing on a planar paper serves the virtual purpose of presentation. Printed drawing and text provide the virtual representation of a physical object. 3D display technologies in a virtual reality environment can provide the vivid impressions of physical objects and their animations. No matter how close the virtual images are made to reality, none of the virtual technologies can produce concrete products until the invention of 3DP [21] and stereolithography [22] etc., which basically push the envelope of 2D printing, a virtual technology in essence, to realize DDM. In a DDM system, a planar printing process is iterated layer-upon-layer to extend to a 3D space. This direct crossing from virtual to real world significantly increases SF and PC while it entails low PR. We can recognize the turning point of this manufacturing revolution when printing as a VM technology converts to a RM technology. The product of VM converts from an image or drawing to a physical part of desirable material so that DDM can circumvent all manufacturing constraints and obstructions in the RM scenario. As basically a printing technology without any conventional challenges of RM, 3DP has almost realized an ideal DDM.

Besides the crossing from VM to RM, equation (10) also covers the other perspective to understand the opposite crossing from RM to VM. Digital formative manufacturing depends on an analog forming process defined by a mold or die. The shaped tool is usually digitally made by CNC machining to enable the analog forming. DDM digitizes the forming process by breaking down the entire volume into discrete layers of identical thickness. As the digitization strength increases significantly, the directness strength of RM increases accordingly to proceed into the realm of VM, in which there is no manufacturing restriction to affect the direct model-to-part conversion.

3.2. The manufacturability leaps by DDM

Three basic metrics, namely SF, PC, and PR, can be again applied to evaluate the manufacturability enhancement of DDM over DM. DDM constitutes a precedence free from the restrictions in tooling, material, and equipment, which had been part of any manufacturing system until DDM is invented. Laser PBF uses an accurate laser beam to realize the energy flow and information flow in DDM. Without a concrete tooling system including cutter, electrode, die, or mold, a laser beam selectively melts powder to convey and convert the geometric information remotely. According to metric equation (1), the SF of DDM can make significant advancement over mere DM since the manufacturing system can readily change and adapt with little tooling challenges and other hardware restriction. In fact, tooling absence and single-step process have significantly increased the SF to an unprecedented level. Such high SF has made rapid prototyping (RP) prevalent and driven the first wave of demand and application expansion [23, 24]. For new product introduction, DDM saves the long lead time and high cost in developing tooling system, processing hardware, and even new equipment among other high-variety and low-count demands. Necessary prototype changes and iterations can proceed quickly and frequently by readily updating product design and manufacturing programs. Substantial hardware introductions and changeovers are no longer involved in the manufacturing system. Sometimes, DDM is often applied to make temporary manufacturing tooling, equipment, and experimental products which are intended only for few or limited number of usages, when product life is not at issue. RP mitigates the investment risk by substantiating the product and technology with much less introduction expenditure. In addition to product prototyping, DDM can benefit other low-volume high-variety production, such as racing automotive parts, customized medical devices, and special large construction structures among other highly customized products. It is not surprising that, for extremely large product with usually low production volume or single piece [25], DDM, especially FDM and 3DP etc., has demonstrated unique benefits in saving cost and lead time. To add more SF, DDM can be programmed to produce intricate geometric features not only on the part surface but also in the part interior while DM is rather limited. DDM does not need system reconfiguration to adapt to various product forms and structures with an almost limitless reconfigurability. While DM adopts a special manufacturing configuration such as turning, milling, forming, or assembly, DDM adopts a general configuration to perform any manufacturing configuration on just one machine and in a single process. Industry has certainly been quick to take advantage of the unprecedented SF. DDM has proliferated to workshops, laboratories, and other various manufacturing sites.

In addition to the much higher SF, DDM makes another significant manufacturability leap in PC to unleash many highly complex product designs. Figure 8 demonstrates a monolithic product design with an outside contour and many intricate internal features, hardly manufacturable without DDM. Some of these internal features allow unprecedented product capability and performance for demanding fluid applications, such as heat exchangers, fuel nozzles, or waste processors among many others. Metric equation (2) measures PC by feature resolution, feature density, and feature intricacy. It is usually more difficult to produce the same complexity internally in the material than externally on the surface. DDM basically balance out manufacturability difference since DDM builds up a part layer-upon-layer and inside out. The additive process can create an out-of-sightline undercuts, blind features, or enclosed cavities because there is no longer issues with tool accessibility and preexisting material obstruction. Without the physical limit of minimal tool tip or dip radius, the sharp definition of high energy sources, such as laser, electron beam, or ultraviolet light, can achieve much higher feature resolution and density than any indirect manufacturing systems that rely on cutters, dies, or molds. DDM and especially 3DP can build extremely small and dense features, down to the scale of micrometers. Complex structures become integrally producible to save the extra stock for joining, fastening, and welding. Figure 8(a), (b), and (c) show printable internal dense features including the cavities, overhangs, and sides of almost arbitrary form, depending on the optimal product function. Casting or molding such features would require impossible tooling features which must dangle and crumble in the forming processes. Figure 8(d) shows the pattern variability in the same layer as well as in different layer for 3DP to allow additional PC with exceptional product performance and value. The significant manufacturability leap in PC has driven the second wave of demand and application expansion. Aerospace and medical device industries among others take the full advantage of DDM capability for *PC*. In aircraft engine, a complex assembly with hundreds of parts can be consolidated into just one complex component and several such components into one unit to reduce engine weight, to enhance engine performance, and to save manufacturing cost [26]. Having succeeded in developing the conglomerate prototypes by DDM, the subsequent volume production can no longer fall back to other advanced technologies to attain a usual productivity. Expect DDM, no other advanced manufacturing technologies have the manufacturability of such extreme *PC*. DDM must carry out serial production beyond prototyping development. The production demand drives capacity increase and business expansion far beyond RP. The serial production of end-user products [27, 28], especially high-quality metal parts, has finally made DDM a volume manufacturing technology beyond just a prototyping technology in a laboratory or development setting. The paradigm shift in product design enables highly integrated devices of unprecedented performance. Difficult-to-manufacturing novel designs such as the new nuclear reactors [29] can be rapidly iterated and validated, free from most manufacturing constraints. Until DDM, it had been frustrating for innovators that many of their ideal designs can only stay as paper products which cannot be manufactured and substantiated. Design for additive manufacturing or DDM has started an era of numerous device possibilities, novel products, and different production paradigms [30].

3.3. The efficacy of DDM depends on directness strength

Conventional manufacturing constraints in material, tooling, and process have been a roadblock to the realization of many novel product designs until DDM becomes available. The digital material and energy flows in DDM clear the material and tooling obstructions to facilitate the direct information flow and conversion in the manufacturing system. DDM makes a step change in enabling the direct convertibility from CAD model as a virtual representation to its physical replica ideally with no information compromise in the conversion. In addition, information complexity challenges the system convertibility. Not all AM modalities are created equal with respect to a conversion directness while information deviation and loss in conversion indicates the weakness in directness strength. Hence, directness strength is referred at as the system capability to allow direct model-to-product conversion by overcoming manufacturing constraints. With the highest directness strength, an almost ideal DDM such as 3DP is still relatively limited in contrast to the almost infinite CAD capability in resolution and complexity. In practice, design tolerances must be set to accommodate the limited directness strength of a manufacturing system. Different modalities have different configurations in information, energy, and material flow as shown in table 3. The directness strength of different modalities is rated according to their respective tool independence, material independence, and information accuracy. The strength scale ranges from 1-3: 1 – low; 2 – medium; 3 – high. The overall directness strength is given by:

$$Directness\ Strength = \sqrt[3]{Tool\ Independence \times Material\ Independence \times Information\ Accuracy} \tag{9}$$

The directness strength of indirect manufacturing systems, though they pertain to advanced DM, can be as low as zero since tool and material independence is equal to zero. Tool and material independence is the earmark of direct manufacturing. However, certain modalities still have some tool dependence. For example, ultrasonic additive manufacturing as sheet lamination can require a cutter to generate the layer contour or 3D outside profile. Binder jetting, material jetting, material extrusion, and DED depend on a nozzle or die of certain diameter to control the deposition extent. Information accuracy is relatively low. Material independence indicates the technology applicability of certain DMM modality to three major material categories, namely ceramics, metals, and polymers. Limited material applicability restricts the directness strength with limited design freedom with respect to material choice. For example, VAT photopolymerization is only applicable to UV sensitive polymer resins. Material extrusion is only applicable to thermoplastics. As a result, the directness strength varies with various DDM modalities. An additive process alone does not guarantee the full directness strength of DDM with respect to the fidelity and freedom of information flow including the information of material specification. As shown in table 3, PBF has the highest directness strength 3 while material jetting has the lowest 1.3.

According to equation (2), the directness strength directly impacts the system manufacturability of PC. The burrowing capability of blind and internal geometric features is of vital value to DDM since no other advanced DM has the unique capability in making the intricate features. Indirect DM entails tool inaccessibility and manufacturing obstruction by preexisting materials. Even for DDM of lower directness strength, such spray type of modalities as material jetting and DED cannot create blind features of detailed definition. The capability of high feature resolution and density is another earmark of DDM, derived from the tool independence and high information definition by laser, electron beam, and ultraviolet sources. Other modalities without the high-definition information flow, such as material jetting, cannot achieve the high feature resolution and density since the information definition is rather limited by the coarse material flow. Hence, the information integrity defined by CAD model and material specs can be compromised in the information flow via its unique information carrier, depending on the different modalities. The carrier can be material jet, material extrusion, or sharp energy beam.

Figure 8 qualitatively shows the manufacturability advancement of DDM by a radar chart with reference to DM and analog mfg. The early RP proliferation has evidenced a significant leap in SF while the later design liberation has evidenced a significant leap in PC. The step advancements of DDM is evaluated against DM, which represents the prior major manufacturability advancements over analog mfg. It is noted that DDM has resulted in no significant or even negative change in PR over DM as DDM has faced with the challenges of unrepeatability and uncertainty in serial production and prototyping fabrication. Despite of the setback in PR, DDM still pertains to a fundamental advancement because it makes significant leaps in two of the three major metrics, namely SF and PC. In general, SF, PC, and PR are mutually competing metrics unless fundamental change, such as DM and DDM, breaks all or most of the rivalries between these different metrics to make simultaneous leaps on two or more metrics. The insufficient PR will be recognized and addressed in section 4.

A system approach must be taken to establish a business case for any DDM application because it enhances SF and PC but not PR. A simple replacement of conventional manufacturing with DDM does not yield cost reduction and quality increase especially when the product is simple in structure and material. System optimization maximizes the overall value of DDM system by maximizing its advantage in SF and PC but minimizing its disadvantage in PR. In the case of RP, the high SF decreases production cost and lead-time in making the low volume and high variety parts while the cost of low PR can be easily offset by the cost of various tooling. The high PC can be used by consolidating components and assemblies to reduce manufacturing processes and cost. In addition, the conglomerate can reduce overall weight and increase efficiency among other performance to add value to the product system. On the hand, the low PR can be improved by transforming DDM as manifested in section 4.

3.4. Identify the virtual attributes and effects of DDM

By adopting a printing setup, DDM makes it possible to circumvent manufacturing constraints in conventional manufacturing system. However, the fundamental switch also leaves an unresolved gap between printing and manufacturing. This gap is the root cause for low PR. Printing as an exhibition technology pertains VM. DDM as a manufacturing technology should pertain RM. But the inherited virtual attributes from printing makes DDM partially virtual. Table 4 compares the two printing scenarios of 2D printing and 3DP, one in the virtual world and the other real world. The two processes of the same root have almost identical system configuration. Their products are rather different to serve very different purposes, one for virtual representation and the other for physical function. The printing configuration serves the purpose of VM well but does not completely satisfy the purpose of DDM as a means of RM.

Table 4 also lists all the virtual attributes relevant to the compromise of PR while comparing the virtual objectives for open exhibition with the real objectives for robust manufacturing. Process openness to surface in printing is definitely necessary for the displaying visibility and clarity. However, the system openness, in a high-temperature fusing process, exposes all the surface material to atmospheric variables. Inert gas protection can chemically prevent oxidation among other surface reactions, but the gas turbulence can mechanically impact powder distribution. The larger the surface area, the greater the demand for gas speed, and the greater the impact to powder surface. A recoating process does nothing but create a new layer of powder, directly imitating the preparation and loading of a new paper in 2D printing. Powder fusing has to pause frequently for powder shoveling and dispensing while only a small portion of recoated area is selected for fusion. The lost cycle time in recoating must be compensated by fast blade motion, which impacts the critical recoating quality. In ink printing on paper, the consistency of ink thickness is not critical as long as necessary contrast is attained to the naked eyes. On the other hand, the surface irregularities of recoating can entail surface waviness and density variation in DDM as a stereo process. By the same token, paper thickness is not critical to the planar printing while irregular powder distribution is a direct cause to variable porosity in a built part. Powder distribution irregularity increases as recoating area and blade speed increase. According to metric (3), the PR of DDM decreases due to the significant increase in system sensitivity, parameter counts, and process extent. In DDM, technology substantiation must cover the integrity of the entire material domain in addition to the usual integrity of part surface and external geometry.

Although the direct crossing from virtual to real world opens up a channel towards the extraordinary SF and PC for DDM, the inherited virtual attributes compromises PR. Direct printing relieves all the conventional manufacturing restrictions, but it also brings in a new set of problems in process variability and controllability. It is necessary to identify and alleviate all the negative impacts of virtual attributes. Process unrepeatability and uncertainty are evident in the practice of DDM especially when maximum part complexity is leveraged in making conglomerate components of jet engines among other demanding products by DDM. Among other inconsistencies, the significant variability in material porosity is a robustness challenge that requires extensive and exhaustive care. Numerous process parameters can make it a time-consuming task to dial in the process for acceptable results; the numerous parameters and extensive processing can give more opportunities for defects and even failures.

4. Reality transformation by Real DDM \ direct 3D building

Besides RM except analog manufacturing, VM is also part of DM for the purpose of virtual demonstration, simulation, and interaction. Unlike RM, VM does not necessarily produce a physical object but only a virtual representation of the physical object. VM has become indispensable in enhancing and optimizing RM performance. Some VM technologies, such as AR and digital twin, can integrate with RM as a powerful system for the best possible manufacturing performance. Ultimately, the VM-enhanced system is still a RM system because it produces physical part or assembly instead of virtual image or drawing. With almost infinite capability in SF, PC, and PR, VM can generate perfect but only virtual products including images and drawings. When the product specifications defined by its virtual representation exceed the manufacturability limits and manufacturing constraints, RM cannot reproduce the virtual product or model in its physically functional form. The concept of DDM is to make a real product directly from its virtual model by bypassing all the manufacturing limits and constraints. Before 3DP [31] printing technology is adopted to make physical part directly, the product of printing including drawings, paintings, and texts was all virtual in nature. Instead of printing, volumetric AM [32] adopted another virtual technology, i.e., imaging, for DDM. While retaining some superior capabilities of the virtual technology, the transition from a virtual technology to a real one in making real physical product has succeeded in bypassing most technological limits and physical constraints in the real manufacturing world. Technological challenges remain. Certain attributes of the adopted virtual technologies can negatively impact the performance of DDM because no virtual technology is originally designed for RM but only for VM. The low PR of DDM should be improved to advance DDM further.

4.1. Characterize RDDM and realty strength

As a manufacturing operation on paper, pixels, or screen, VM is a simulative implementation of RM in the computer environment. The product of VM can be images, drawings, 3D models, and specifications among other virtual data form as opposed to physical and functional parts only RM can produce. Figure 9 includes RM and VM among other relevant scenarios under the broad umbrella of DM.

$$DM = VM \cup RM \cup DDM \cup RDDM \qquad (11)$$

Equation (11) captures all subsets of DM including the new one of real DDM (RDDM). VM can conduct comprehensive process and product simulation in a virtual environment far beyond what can be physically experimented in real world. On the other hand, RM produces functional parts for end user application rather than just for model demonstration or prototyping. Equation (10) indicates DDM is the intersection of RM and VM. DDM made a step change in directness strength but the introduced virtual attributes compromise PR in fulfilling the purpose of RM. In addition to digitization strength and directness strength, reality strength is introduced to evaluate the system settings for RM rather than VM. The more the virtual attributes, the lower the reality strength. The pervasive development of VM including virtual reality has confounded the distinction between RM and VM despite of their different manufacturing purposes. DDM creates a scenario of mixed purposes but its outcome is still measured in real metrics.

AS for DDM\3DP, table 5 lists the potential virtual attributes, their original need in printing, their negative effect on 3DP, and reality gap between printing need and negative effects. Prefabricated papers dictate the material flow of 2D as well as 3D printing although there is no paper in 3DP. The information definition of build form is carried by either laser beam or ink jet in 3DP which simulates the information and energy flow in 2D printing on paper. In 3DP, the information carrier turns out to be the laser beam for laser PBF. Hence, the reality gaps emerge since 3DP structurally and systematically simulates the printing setup. The negative impacts of the virtual attributes entail reductions in both PR and productivity.

The prevalent strategy to the challenge [33] follows an approach of reactive improvement while allowing DDM stuck with the virtual setup and attributes. RDDM adopts the strategy of fundamental improvement by making a realization transformation to the virtual attributes. Fundamental change aims at problem elimination while reactive improvement relies on the solutions to compensate the problem. Effective solution depends on a thorough understanding of the complex problem which involves many virtual effects and their complication to an extensive recoating and fusion process. First, the complex material flow in fusion and distribution is directly detected and viewed by high-speed X-ray and thermographic imaging [34, 35] among other high-tech inspection technologies. Second, multi-scale and multi-physics modeling [36,37] has to be applied to correctly simulate the complex and extensive building mechanisms. Appropriate AI needs to be developed and trained to grasp the process behavior unless the most powerful modeling turns to be inadequate. Big data must be developed in addition to AI and exhaustive modeling. Last, operando characterization, modeling, and control are also proposed with the best computing power available. Still, the exact efficacy is not guaranteed. Hence, the mentioned fundamental change is highly desirable to untangle the complexity. The new paradigm is referred to as real DDM (RDDM), transforming DDM into a RM technology. The resultant system of RDDM will make another step change in the already most state-of-the-art manufacturing system of DDM. The goal is to increase the reality strength of the manufacturing system while retaining or even increasing its directness strength and digitization strength. Similar to DM and DDM, RDDM is a differentiation to DDM to make another significant leap in manufacturability and especially PR. Figure 9 indicates RDDM progresses towards the ideal point of the highest reality strength and directness strength. RDDM increases the reality strength by changing or realizing the virtual features carried over from a conventional printing system. Such a realization transformation from DDM to RDDM demands innovative system configurations in an uncharted territory as shown in figure 9.

Figure 10 shows a development cycle from conceptual design to volume production. The reality strength of the technology applied in each stage rises as the product evolves with an increase in product quality. In design idealization, blueprint, and 3D solid model, the product form emerges and develops in all virtual environment of CAD, CAM, and VM. The reality strength and product quality remain at zero. When the product proceeds to a 3D printed demo plastic model, the reality strength remains at zero. At this point of DDM, 3DP serves only the virtual purpose of model exhibition like drawing on paper or image on screen. Product quality is greater than zero but not adequate for real function. Next, a printed metal prototype can have the adequate product quality but only for a temporary period of experiment. A 3DP production part attains more quality and reality strength than the prototype after production development and substantiation. Since 3DP as a DDM system is still limited by the virtual effects, its reality strength and product quality cannot achieve full capacity. Poor PR indicates the lack of product quality due to the low reality strength of DDM system. RDDM system will make another step change in product quality as system reality leaps after the realization transformation of RDDM.

4.2. Innovate direct 3DB as a reality transformation of 3DP

Table 3 indicates 3DP including laser PBF, binder jet, and VAT photopolymerization attains the highest directness strength. This research and development of RDDM focuses on 3DP and especially laser PBF as the DDM modality of the highest directness strength. The strategy is to increase PR by enhancing reality strength under the constraints of retaining or even improving the directness strength whenever possible. Hence, the goal is another fundamental advancement in all three metrics of manufacturability, namely SF, PC, and PR, rather than increasing one of them at the expense of other two.

Laser PBF basically consists of two steps, i.e., powder dispensing and selective fusing. While the latter has attracted more research attention and effort, the former turns out to be more critical to PR due to the inadequate powder uniformity and density [38]. Once powder recoating completes, laser parameters in the fusion process cannot compensate the deficient packing density, packing density variation, and recoating thickness variation, which entail build porosity. Certainly, energy flow cannot compensate the insufficient material flow that precedes the laser fusion process. On the other hand, the selective fusion on powder surface, driven by the defined energy flow of laser beam, has its own problem due to the extensive exposure to gas turbulence, moisture, spattering, and/or other atmospheric variables. Both problems can be attributed to the lack of reality strength in the 3DP system because the manufacturing system is based on 2D printing as a virtual system. Table 5 lists the negative effects of virtual attributes on 3DP with the purpose of RM. The reality transformation of 3DP does nothing but diminishing all the virtual attributes.

Figure 11 demonstrates and elaborates a reality transformation from DDM to RDDM, in which 3DP changes to 3D building (3DB). Inside the hollow ram, a laser beam selectively scans and fuses the powder surface as in 3DP. However, the ram and process are submerged in powder. The powder tank translates in X-Y plane while a blade at the front bottom edge of the ram extrudes a flat and horizontal powder layer at the ram bottom end. Selective laser fusion, powder tank translation, and powder layer extrusion are three concurrent processes in the manufacturing system. Separate recoating in 3DP is saved along with the long blade or roller. Once all the geometrical patterns on the current layer are fused, the powder tank shifts down in -Z by a programmed increment to start processing the next layer. Such cycle continues until the build reaches the top of part program.

This system configuration of RDDM minimizes the process openness to surface as the first virtual attribute inherited from 2D printing. Unlike printing on paper, manufacturing process does not need to stay on the top surface for clear and unobstructed visibility. Small atmospheric volume inside the hollow ram becomes much more manageable by protection gas such as nitrogen or inert gas. Vacuum inside the limited ram space becomes another feasible option. Unlike in 3DP, a separate recoating process, in which powder particles are shoveled by a wide blade or roller from one end to the other, is no longer necessary. Powder recoating inherits the other virtual attribute from printing by spreading a layer of powder on the entire top surface of the powder tank despite the part extent to be fused. This extensive process in printing basically creates a new blank paper or removes an already printed one before another page can be printed. This separated process is not necessary for RM purpose since there is no need for papers. 3DB saves the frequent recoating pauses in 3DP by synchronizing the three processes of selective fusion, tank translation, and coating extrusion. Since recoating takes place every layer, total manufacturing time saved without the frequent recoating is very significant. Driven by CNC, the tank translation allows laser ram to cover only the surface area to be selected in laser fusion while skipping large blank area. 3DB saves considerable recoating work while reducing the challenges to recoating quality. In this RDDM, 3DB transforms the two major virtual attributes in 3DP, i.e., process openness to surface and frequent powder recoating, in order to increase the reality strength significantly. Hence, 3DB pertains to RDDM as 3DP pertains to DDM. Other RDDM transformation can be devised by following the same realization strategy.

4.3. Leaping advancements by RDDM\3DB

Following the methodology of RDDM, 3DB transforms the two virtual attributes in 3DP to increase the system reality strength while retaining or even improving the directness strength. In this case, both 3DB and 3DP are in the same scenario of laser PBF but their reality strengths are different. The enhancement in reality strength can be translated into manufacturability advancement especially in PR.

4.3.1. Diminish exposure to many atmospheric variables

Process submersion in powder bed diminishes the extensive exposure to many atmospheric variables in 3DP. Moisture and oxygen can significantly impact the material quality unless protection gas is applied. In 3DP, the volume flow speed of inert gas or nitrogen must be increased to cover a large surface area including corners and other zones difficult for the gas to reach. However, the strengthened gas flow can disturb the powder stability and recoating consistency. Submerged in powder, 3DB only needs a limited volume of gas flow inside the ram to provide the necessary isolation from all the atmospheric variables. 3DB permits gas concentration only on the selected fusion zone rather than a complete coverage of the entire powder-bed surface including far corners among other difficult zones. From equation (3), the process submersion reduces system sensitivity to atmospheric chemical attacks to the build material by constraining the input of moisture and oxygen among others. 3DB allows a limited process extent to decrease the gas variation as far as gas velocity and pressure are concerned. Gas variation and its coverage increase as the total flow area increases. Without the need to cover corners and difficult zones, the extra gas speed is no longer necessary. The lower but adequate gas velocity does not impact powder stability and recoating consistency so that 3DB eliminates the significant process variable. The reduction in system sensitivity, process extent, and parameter count contributes to the enhancement of PR according to equation (3). Besides the increased PR, the significant reduction in gas volume speed saves the consumption and cost of indirect material while improving the product quality. Since the selective laser fusion only affects a small area of powder surface for a given instant, it is a waste for the protection gas to cover the entire powder-bed surface with such fast and extensive gas flow. To increase the reality strength significantly, 3DB diminishes the process openness, which 3DP inherits from 2D printing and serves the purpose of virtual imaging. The high reality strength results in high PR in addition to the bonus benefit of the reduced gas consumption and cost.

4.3.2. Improve powder uniformity and density – Figure 12 shows 3DP and 3DB have different mechanisms in creating a level powder layer. The long blade of 3DP shovels and spreads powder to cover the entire powder bed surface while a short blade in 3DB accurately extrudes a powder layer only to cover the surface inside the ram. The blade of 3DP shown in 12(a) must scan fast across the large area while selective fusion pauses for it; otherwise, the cycle time drastically increases with typically many thousands of layers to be built. Moderate blade speed yields high powder uniformity and packing density [39]. High blade speed, desirable for high productivity, increases the instability in shoveling and spreading the powder from supply tank to the entire powder bed surface. The result includes not only lower packing density but also thinner recoating than the set thickness. As shown in 12(b), 3DB can afford lower blade speed as to attain better powder uniformity, packing density, and layer thickness as there is no recoating pause in 3DB. The selective fusing process concurs with the generation of level powder surface by a front blade edge of machine ram. Given the same building speed or productivity, the blade of 3DB can move slower and more steadily than the blade of 3DP. Unlike 3DP, 3DB does not need to distribute and level the powder over the entire powder bed surface but just to level the material inside the limited ram area. Powder flowability is much less critical for 3DB than 3DP because the powder shoveling and spreading for 3DP demand much better powder flowability than the powder extrusion for 3DB. Under compression, the extrusion process produces powder layer with higher packing density and powder uniformity in terms of less variation in layer height and density. To attain the same density and uniformity, powder relocation and distribution are much more challenging than powder extrusion. From equation (3), the different powder preparation mechanism of 3DB significantly changes the high system sensitivity of 3DP to process variability to increase PR. Blade speed and powder flowability are no longer among the critical parameters to powder layer quality to cut parameter counts by 2. In addition, the process extent of 3DB is less than 3DP. Hence, the reduction in system sensitivity, parameter counts, and process extent contributes to the enhancement in PR. Higher powder layer quality results in lower build porosity, porosity variability, and other variations in material and form. As a realization differentiation to DDM\3DP, the RDDM\3DB eliminates the printing step of creating a blank page by material loading or recoating. PR increases significantly when the virtual attribute is replaced by the appropriate mechanism for real manufacturing. Besides the gain in PR, the transformation brings in one more bonus benefit in material cost. In contrast to powder relocation and distribution, the powder extrusion reduces the critical material requirement to powder flowability concerning certain particle morphology and size tolerance. As a result, powder cost can be reduced without the tight tolerance to particle shape and size. In addition, smaller particles are permitted in the mix to fill the voids between larger particles to further increase packing density.

4.3.3. Eliminate printing redundancies and their implications – 3DB cuts the significant process redundancies in 3DP by eliminating the separate recoating step. Powder recoating in 3DP requires 4 operations as the building operation for actual value addition must pause.

- Supply piston rises to move adequate powder above blade edge.
- Build piston descends to set recoating thickness.
- Powder blade shovels and distributes powder from supply tank while excess powder goes to overflow tank.
- Powder blade translates all back from overflow tank to the origin to prepare for the next recoating cycle.

In 3DB, powder surface preparation and following selective laser are synchronized to save the considerable time for separate and frequent recoating. Recoating time adds up rather quickly since it has to happen for every layer. If each recoating cycle takes 4 seconds and entire build consists of e.g., 2000 layers, the recoating time alone takes over 2 hours. 3DB can save all the recoating time since powder layer preparation concurs with selective fusion. 3DB saves the considerable work and time in powder relocation and redistribution by just extruding the pre-allocated powder in the tank.

As shown in figure 13, usually only a fraction of the entire leveled area is selected for fusion while a large part of the recoating is blank. The recoating work for blank area is basically a waste. On the other hand, the machine ram of 3DB can skip the large blank area and only cover the area with features to be fused and built. Hence, 3DB can save the waste in work and time. In addition, powder uniformity is much more difficult to maintain on a large surface area in 3DP than a small one in 3DB. Blade deflection and vibration impact recoating quality in practice with a large powder bed. The limited powder flowability prevents uniform powder distribution across the long blade width especially. Nonuniform powder distribution leads to locally low packing density and material porosity in the built material. 3DB fundamentally alleviates the nonuniformity situation by basically reducing the process extent defined in equation (3). First, short blade width makes powder flowability less critical. Second, powder extrusion does not need the lateral particle flow as much as in the powder recoating.

The reality transformation by RDDM\3DB changes the material flow of DDM\3DP to cut redundancies for manufacturing and to increase PR at the same time.

4.3.4. Material improvements by 3DB – Metal 3DP by selective laser fusion or melting entails columnar grains in the vertical building direction [40]. This microstructural anisotropy entails stress buildup and potential cracks. As shown in figure 14, the machine tank or ram in 3DB can rotate or tilt to change the building direction. Alternating building direction interrupts the elongated grains and cancels the material anisotropy to some extent. It is also possible to leverage the strength advantage in the elongation direction by aligning the building direction with the direction to which the maximal stress occurs in part service. The building direction is adjustable by tilting the orientation of either machine ram or powder bed. Unlike 3DP, building direction can vary in 3DB.

In addition, 3DB limits its build extent inside the machine ram to prohibit a long or large resolidified layer, which can entail part distortion and catastrophic crack. Stress in the large, resolidified layer after selective fusion can build up rather rapidly to part failure. Given a large cross section by part design, 3DP divides a large recoating layer into a checkerboard for the progression of laser scanning and hatching [40] to prevent stress the buildup. 3DB has built in the checkerboard strategy in the system since the limited extent of machine ram does not allow long and continuous resolidified traces of high stress and distortion.

From equation (1), this new programmability of building direction increases the SF of 3DB over 3DP. This new SF can also facilitate the termination of continuously built material and internally built-up stress to limit the process extent. Hence, PR can be increased by the reduction in process extent according to equation (3). RDDM can enhance not only PR but also SF.

4.3.5. Incorporation of extrinsic components and materials – Figure 15 shows a unique SF of 3DB in incorporating a center shaft in a complex build. Actually, multiple premade components can be integrated with the main build. The extrinsic shaft can have an accurate center bore which is machined and prepared before 3DB. Selective laser fusion cannot attain the high accuracy and surface finishing for a machined shaft to fit snugly to a spindle or bearing among other precise parts. Hence, the manufacturability of integral part building opens up many interesting possibilities by DDM after the transformation of RDDM. Figure 15 shows a built-in center shaft just for instance, but the built-in part can locate outside or below the complex build to be made in 3DB. Multiple parts can be built in the same manner. In addition to the precise geometry and high surface finishing, the extrinsic components can be made of various different materials to constitute a composite and complex structure by 3DB. It is noted that the recoating blade of 3DP prevents any pre-allocated component in the build volume because it can interfere with the scanning blade in powder recoating. Without the extensive recoating scan by the blade, 3DB can accommodate the extrinsic part in the build volume. Hence, 3DB enhances the PC including different materials and special structures in the same complex build. The increase in reality strength can enhance not only PR as expected but also PC and SF as the other two manufacturability metrics. It is evident that such a reality transformation of DDM to RDDM makes a fundamental leaping advancement in manufacturability because of the resultant enhancements in all three metrics rather than the usual relative improvement of one metric at the expense of other two.

5. Conclusion

Evaluated by three mutually competing and independent criteria, i.e., SF, PC, and PR, the overall system manufacturability has become the objective of all major modern manufacturing advancements. Only fundamental enhancements, such as DM, DDM, and RDDM, can make a significant leap on at least 2 or all 3 criteria in the metric. The essence of AM is DDM, which has driven the successes in rapid prototyping and most recently serial production for end users. 1st paradigm shift from analog manufacturing to DM has made a significant leap in all three criteria. The higher the digitization Strength, the greater the manufacturability gain a particular DM technology can attain. As an extreme scenario of DM, VM attains full digitization strength but produces no physical part. DM is limited in SF and PC until DDM is developed.

Inspired by the infinite digitization and directness strength of VM, inventions have been made to transform a virtual exhibition technology, such as dot-matrix printing, into a physical manufacturing technology, such as 3DP. The 2nd paradigm shift from DM to DDM has also made a significant leap but only in two of the three criteria, i.e., SF and PC. In DDM, the enhancement in SF and PC increases as the directness strength increases. However, PR declines as the introduced virtual attributes reduces the reality strength.

To compensate the lower PR, RDDM transforms DDM, the most state-of-the-art manufacturing technology so far, by identifying and removing its critical virtual attributes to increase the reality strength. RDDM makes a necessary step change in the PR of DDM while retaining or even improving its SF and PR. The higher the reality strength of RDDM, the less the system is subjected to the process uncertainty due to the inherit virtuality. The challenge is for RDDM to remove all the introduced virtuality without an impact to the directness strength.

3DB demonstrates a practical design of RDDM which transforms 3DP as one of the original DDM modalities. Instead of reactive compensations, 3DB makes fundamental changes in the 3DP structure. In 3DB, the process submersion in powder alleviates the extensive exposure to atmospheric variabilities. To attain uniform and dense powder distribution, 3DB turns the difficult powder shoveling and dispensing in 3DP recoating into a more robust and precise powder extruding process. Instead of reactively compensating the inherent variabilities by an operando control system, 3DB per RDDM methodology fundamentally changes the virtual setup of 3DP to diminish the inherent variabilities.

3DB brings other benefits in addition to a step change in PR. As a lean transformation, the selective fusion is synchronized with the powder extrusion coating to save the frequent pauses in the powder recoating of 3DP. Also, the process is able to skip large unfused or blank areas to save the significant amount of work in powder leveling and coating. 3DB further enhances the SF and PC of 3DP, already the most powerful so far among all advanced manufacturing systems, by enabling the incorporation of extrinsic components and materials into its fused-powder build.

6. Nomenclature

2D – 2 dimensional

3D – 3 dimensional

SF – system flexibility

PC – product complexity

PR – process robustness

AM – additive manufacturing

DM – digital manufacturing

DMLM – direct metal laser melting

VM – virtual manufacturing

RM – real manufacturing

AI – artificial intelligence

AR – augmented reality

DT – digital twin

VR - Virtual reality

IIoT – industrial internet of things

DDM – direct digital manufacturing

RDDM – Real direct digital manufacturing

PBF – powder bed fusion

Mfg. – manufacturing

NC – Numeric control

CNC – Computer numeric control

CAD – computer aided design

CAM – computer aided manufacturing

3DP – 3D printing

3DB – 3D building

R&D – Research and development

7. References

1. Wohlers Associates, Inc., 2013, Wohlers Report 2020: Additive Manufacturing and 3D Printing State of the Industry, Wohlers Associates, Fort Collins, CO.
2. ASTM, 2009, ASTM International Committee F42 on Additive Manufacturing Technologies, ASTM F2792–10 Standard Terminology for Additive Manufacturing Technologies, ASTM, West Conshohocken, PA.
3. ISO/ASTM 52900: 2015 Additive manufacturing — General principles — Terminology
4. Yong Huang, Ming C. Leu, Jyoti Mazumder, Alkan Donmez, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations," ASME Journal of Manufacturing Science and Engineering, FEBRUARY 2015, Vol. 137 / 014001, 1-10.
5. Danfang Chen, Steffen Heyer, Suphunnika Ibbotson, Konstantinos Salonitis, Jon Garðar Steingrímsson b, Sebastian Thiede, "Direct digital manufacturing: definition, evolution, and sustainability implications," Journal of Cleaner Production, 107 (2015), 615-625.
6. Kruth J P, Leu M C, Nakagawa T. "Progress in additive manufacturing and rapid prototyping," Annals of CIRP, 1998, 47(2): 525- 540.
7. L.E.J. Thomas-Seale, J.C. Kirkman-Brown, M.M. Attallah, D.M. Espino, D.E.T. Shepherd "The barriers to the progression of additive manufacture: Perspectives from UK industry," International Journal of Production Economics, 198 (2018) 104–118.
8. L. Dowling, J. Kennedy, S. O'Shaughnessy, D. Trimble, "A review of critical repeatability and reproducibility issues in powder bed fusion," Materials and Design,186 (2020) 108346
9. Ma L, Fong J, Lane B, Moylan S, Filliben J, Heckert A, et al. "Using design of experiments in finite element modeling to identify critical variables for laser powder bed fusion," Solid Freeform Fabr Symp Proc 2015:219–28.
10. Zhao, C., Fezzaa, K., Cunningham, R.W. *et al.* Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction. *Sci Rep* **7,** 3602 (2017). https://doi.org/10.1038/s41598-017-03761-2
11. Leung, C.L.A., Marussi, S., Atwood, R.C. et al. In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing. Nat Commun 9, 1355 (2018). https://doi.org/10.1038/s41467-018-03734-7
12. Raplee, J., Plotkowski, A., Kirka, M. *et al.* Thermographic Microstructure Monitoring in Electron Beam Additive Manufacturing. *Sci Rep* **7,** 43554 (2017). https://doi.org/10.1038/srep4355
13. Koren, Y., Gu, X. & Guo, W. Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng. 13, 121–136 (2018). https://doi.org/10.1007/s11465-018-0483-0
14. Zude Zhou, Shane Xie, Dejun Chen, "Fundamental of digital manufacturing science," Springer-Verlag Landon Limited 2012.
15. "Digital Manufacturing: The Factory of the Future is Here Today," Industry Week, Jan 10, 2017.
16. Parsons J T, Stulen F L. US Patent 2820187, 1958-01-14

17. A. de Toni and S. Tonchia, "Manufacturing Flexibility: a literature review. International Journal of Production Research," 1998, vol. 36, no. 6, 1587-617.
18. Wang, Y., Huang, Y., Cao, J. and Reddy, N.V. (2008) "Experimental Study on a New Method of Double Side Incremental Forming", Proceedings of the 2008 International Manufacturing Science and Engineering Conference, MSEC2008, October 7-10, 2008, Evanston, Illinois, USA.
19. Yuefeng Luo, Nouman Usmani, et al. US Patent 10,953,483 B2, Mar. 23, 2021.
20. J. Novak-Marcincin, J. Barna, M. Janak, et al. "Augmented Reality Aided Manufacturing," Procedia Computer Science, 25(2013), 23–31.
21. Emanual M. Sachs, et al. US Patent 5,204,055, "Three dimensional printing techniques," 04/20/1993.
22. Charles Hull, US Patent 4,575,330, "Apparatus for production of three-dimensional objects by stereolithography," 03/11/1986.
23. Detlef Kochan, Chua Chee Kai, Du Zhaohui, "Rapid prototyping issues in the 21st century," Computers in Industry, 39 (1999) 3–10.
24. D.T. Pham, R.S. Gault, "A comparison of rapid prototyping technologies," International Journal of Machine Tools & Manufacture, 38 (1998) 1257–1287.
25. Alex Roschli, Katherine T. Gaul, et al., "Designing for Big Area Additive Manufacturing," Additive Manufacturing 25 (2019), 275-285.
26. Shahir Mohd Yusuf, Samuel Cutler and Nong Gao, "Review: The Impact of Metal Additive Manufacturing on the Aerospace Industry," MDPI, Metals 2019, 9, 1286.
27. Markus Seibold, "Additive Manufacturing for Serial Production of High-Performance Metal Parts," Mechanical Engineering, Vol.141, Issue 05, May 2019, 45-50.
28. C. Emmelmann, J. Kranz, D. Herzog, E. Wycisk, "Laser additive manufacturing of metals," in: V. Schmidt, M.R. Belegratis (Eds.), Laser Technology in Biomimetics, Springer, Heidelberg, 2013, 143-161.
29. Michael Abrams, "3D Printing Goes Critical with Nuclear Reactor Core," Vol.142, Issue 09, Sept 2020, 45-50.
30. Mary Kathryn Thompson, Giovanni Moroni, et al. "Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints," CIRP Annals – Manufacturing Technology, 65 (2016) 737-760
31. Emanual M. Sachs, J. S. Haggerty, M. J. CimaPaul A. WilliamsUS Patent 5,204,055, "Three dimensional printing techniques," 04/20/1993.
32. B. E. Kelly, I. Bhattacharya, H. Heidari et al, "Volumetric additive manufacturing via tomographic reconstruction," Science 2019, 363, 1075−1079.
33. G. Tapia, A. Elwany, "A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing," ASME Journal of Manufacturing Science and Engineering, Dec 2014, 136(6): 060801.
34. Leung, C.L.A., Marussi, S., Atwood, R.C. *et al.* In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing. *Nat Commun* **9,** 1355 (2018). https://doi.org/10.1038/s41467-018-03734-7

35. R. Dinwiddie, R. Dehoff, P. Lloyd, et al. "Thermographic in-situ process monitoring of the electron-beam melting technology used in additive manufacturing," Proceedings of SPIE 8705 - The International Society for Optical Engineering, 22 May 2013
36. C. Herriott, X. Li, N. Kouraytem, et al. "A multi-scale, multi-physics modeling framework to predict spatial variation of properties in additive-manufactured metals," Modelling Simul. Mater. Sci. Eng. 27 (2019) 025009 (23pp)
37. W. Yan, W. Ge, Y. Qian, et al. "Multi-physics modeling of single/multiple-track defect mechanisms in electron beam selective melting," Acta Materialia, 134 (2017) 324-333
38. C. Meier, R. Weissbach, J. Weinberg, et al. "Critical influences of particle size and adhesion on the powder layer uniformity in metal additive manufacturing," Journal of Materials Processing Tech., 266 (2019) 484–501
39. T. -P Le, X. Wang, K. P. Davidson, "Experimental analysis of powder layer quality as a function of feedstock and recoating strategies," Additive Manufacturing 39 (2021) 101890
40. J.-P. Kruth, M. Badrossamay, E.Yasa, et al. "Part and material properties in selective laser melting of metals," Proceedings of 16th International Symposium on Electro-machining (ISEM XVI), April 2010, 3-14.