Sanjay Kumar

Hybrid Additive Manufacturing Debate

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For permissions, contact:
Email: skumarsdr@gmail.com

About the Author

Dr. Sanjay Kumar is the author of the following recent publications:

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- Additive Manufacturing Classification, 2022, Springer https://www.springer.com/book/9783031142192

- Additive Manufacturing Advantage, 2023, Springer https://link.springer.com/book/9783031345623

- A New Theory of Additive Manufacturing, 2024, Springer https://link.springer.com/book/9783031754265

- A Concise Encyclopedia of Additive Manufacturing, 2025, Springer https://link.springer.com/book/9783031983931

- A New H-index, 2025, Scholarly Dialogues Press https://www.google.com/books/edition/A_New_H_index/JM2bEQAAQBAJ/

- Additive Manufacturing Debate: A Thought Experiment, 2025, Scholarly Dialogues Press https://www.amazon.com/dp/B0GCFT5DV5

Preface to the Revised Version

An appendix named ‘Industrial Executive Summary’ is added. It contains a logical decision tree.

Sanjay Kumar
29 August 2026

Preface

There are two terms in additive manufacturing (AM): shaping and post-processing. These are so prevalent that everyone knows and uses them when required. This has led to their use for different purposes, giving rise to not a single meaning for each term. This has brought into question how much post-processing is acceptable to define AM. This question is tied to another question: what AM stands for—making either all parts or increasingly complex parts. The aim is to answer these questions.

The merits of these questions can be better understood if opposing views are instantly available to argue from both sides. Therefore, the present book is written in the form of conversations between two imaginary researchers, named R1 & R2, emphasizing storytelling. It is divided into two parts. The first part consists of five sections; the second one, four sections. These sections are titled Dialogue 1 to Dialogue 9. There are 726 conversations that are continuously numbered. Numbering allows them to be tracked independently of a section number. References for all sections are given together at the end.

The title 'Hybrid additive manufacturing debate' implies that the conversations are only about hybrid AM (HAM), but this is how it started. Therefore, the first section, i.e., Dialogue 1, is named Hybrid AM. After that, the conversations involved several questions that are not confined only to HAM. Some of the questions are related to the following: the role of post-processing, how much post-processing converts AM into HAM, the difference between simple and complex parts, how to define a complex part, which parts should be preferred in AM, which particular problem defines AM, how AM is different from other techniques, why simple parts should not be fabricated using AM, how the boundary between AM and HAM can be defined, what is the role of AM in shaping, what is shaping, what is the role of manufacturing, is there any difference between AM and an AM process, is AM near-net-shaping technology, is a part sustainable, etc.

The conversations, heated exchanges, arguments, counter-arguments, examples, counter-examples, agreement, and disagreement led to a conclusion. The conclusion is that a structural framework is needed—one that defines the external and internal boundaries of AM. The external boundary is to distinguish AM from HAM; the internal one, simple shapes from complex shapes.

The framework titled 'Twin-boundary framework for AM' is presented in Part 2. The framework has two boundaries or pillars. Dialogue 6 informs about it. Dialogue 7 gives its general description. Dialogues 8 & 9 give detailed descriptions of the first and the second boundary, respectively. The conversations that led the framework are given in Part 1. Dialogue 2 deals with the meaning of shaping. Dialogue 3 tries to reason why AM should be treated differently from other techniques. Dialogue 4 discusses why simple AM parts should not be made and when they should be made. Dialogue 5 reasons the same from a sustainability perspective.

The conversations sometimes go slow, but it helps when the logic is counterintuitive. I hope this book will be helpful to everyone.

Gumla, Jharkhand, India   Sanjay Kumar
13 August 2026

Contents

PART 1

Before Framework

Dialogue 1

Hybrid AM

1 **R1**: What are you doing these days?

2 **R2**: I have developed a hybrid additive manufacturing (HAM) machine.

3 **R1**: Can you describe?

4 **R2**: I have integrated a milling tool in a directed energy deposition (DED) [1] machine. The purpose of integration is to overcome the limitations of DED [2]. The tool removes material from horizontal and side surfaces made by DED, which decreases deformities while improving surface accuracy [3]. It also removes residual stress and improves properties [4-5]. We talked about HAM last time [6].

5 **R1**: Can you give an example of how you use the hybrid machine?

6 **R2**: I get a surface roughness of 50 µm when I print a part. I machine it afterward so I get a high surface finish.

7 **R1**: This is not HAM.

8 **R2**: Why?

9 **R1**: What you did is post-processing. You did not change the shape or size of a part. Therefore, the combined process of DED and machining is not HAM.

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10 **R2**: If it is not HAM, what is it?

11 **R1**: DED

12 **R2**: But I used machining as well.

13 **R1**: The contribution of machining is not enough to change the final process.

14 **R2**: Can I say, ‘My combined process is DED plus machining.’

15 **R1**: Yes, you can.

16 **R2**: But you have just said it is DED.

17 **R1**: You can say it is DED, AM, AM plus machining, AM plus post-processing, DED plus machining, or DED plus post-processing. But you must not say it is HAM.

18 **R2**: Why?

19 **R1**: This is how confusion is created.

20 **R2**: I do not understand your logic. Combining AM and post-processing means making the hybrid of AM and post-processing. Therefore, we should also say the combination is a hybrid one.

21 **R1**: This is how our common sense creates confusion.

22 **R2**: Please define HAM.

23 **R1**: HAM is a process in which the shape of a part is formed using AM and at least one manufacturing technique.

24 **R2**: But I got the final part shape by machining.

25 **R1**: No, you did not get the final shape by machining; you got a final finish by machining. The original dimension of the part was given by DED, which was unchanged by machining. The original dimension is the shape of your part.

26 **R2**: But to get a fine finish, I had to decrease the part size by machining [7].

27 **R1**: This does not come under a size change.

28 **R2**: You are missing a point. Should I explain?

29 **R1**: Yes.

30 **R2**: First, the DED machine was at one corner of my workshop and the milling one at another corner. At that time, I used to make two CAD models. First, I used one model at DED, and then I would go to the milling one to use another model. I had a difficulty in positioning the part and moving frequently between two machines. Presently, I have combined the two. For combining, I had to fix the position of the spindle of the milling machine and the nozzle of the DED so their coordinates would match. I had to develop software to get my work done using only one model. I call my machine HAM because it gives me the convenience of working, while the results provided by it are efficient and fast. If you still do not call it HAM, where is the reward for my hard work?

31 **R1**: You are confusing a machine with a process. A process is defined by what your machine does, not what your machine is. You did DED plus post-processing; therefore, it is called DED. If it had been done by separate machines, it could have been called the same. What you got is the convenience of working, not the right to change what HAM is.

32 **R2**: I just inform you that I have patented my machine, stating that the machine is for the HAM process.

33 **R1**: It only means your machine can execute the HAM process, which other machines, such as DED, cannot.

34 **R2**: It is wrong. Let me repeat that a combination of two machines is HAM, not what precisely the effect of the combination is. It is because the combination is defined as HAM [8].

35 **R1**: There is no standard definition for HAM. It is not about the effort; it is about the result. It is not about the input; it is about the output from that input.

36 **R2**: Are you saying post-processing is a problem?

37 **R1**: What you did with the post-processing is a problem.

38 **R2**: What is the role of post-processing [9]?

39 **R1**: It is not meant to change the shape and size of a part.

40 **R2**: What if it changes?

41 **R1**: Then, it is HAM.

42 **R2**: Can you explain what constitutes a change?

43 **R1**: Let us consider you have used DED to make a 2 cm diameter, 10 cm height cylinder. If you use post-process machining to decrease its height to 9 cm, you are changing the size. Since this size change alters the aspect ratio of the cylinder, it changes its shape as well. Your process is HAM.

44 **R2**: What if it does not change the shape? For example, if the height is changed to 5 cm and the diameter to 1 cm

without affecting the aspect ratio, the shape is still a cylinder.

45 **R1**: It is again HAM because the size changes.

46 **R2**: Can you explain what does not constitute a change?

47 **R1**: This is what you did, i.e., using post-process machining to remove 50 μm Ra surface roughness of a DED part.

48 **R2**: To remove it, I need to remove 1 mm thick material. It is not possible to eliminate it without removing the extra material. This is the only way surface roughness is removed by machining. The moment I remove the material, the size of the cylinder becomes smaller. How do you say the cylinder size will not change?

49 **R1**: How do you print?

50 **R2**: To make a 2 cm diameter, 10 cm height cylinder, I print a cylinder of 10.1 cm height. The extra height of 0.1 cm is a material allowance. After machining, the height decreases from 10.1 cm to 10 cm. Is this decrease not a change in the cylinder size?

51 **R1**: The core dimension of the cylinder is 2 cm x 10 cm. The question is whether this dimension you can get only using AM. If the answer is yes, the process is AM. In your case, you are able to get this dimension; therefore, the process is AM.

If you need to remove surface roughness, this removal does not constitute changing the original dimension. If the removal process changes the original dimension, this does not disprove the ability of AM to make the original dimension. Because what comes first is the making of the original dimension and what comes later is the removal.

Therefore, what will come later will not change the history that has already happened.

If extra material needs to be removed to remove the roughness, there lies a problem in your method to remove the roughness. It is not the demerit of the shaping capability of AM if the surface removal operation cannot work independently without interfering in the original dimension. It is just like blaming a machining operation for the faulty design of a clamp if the clamp requires an extra size of a workpiece to hold for the smooth functioning of the operation.

Besides, it is not for AM to provide a high surface finish. If it provides, that is a bonus. If it does not, it is still AM. Providing less surface finish does not deprive AM of its shaping ability. If I say AM is not for providing a fine finish, do not blame me that I am not encouraging a fine finish to be obtained by AM. What I am saying is that you must distinguish between the essential and the desirable requirements for AM.

In your case, you have added extra material of 0.1 cm; this again shows that AM has not only shown its shaping ability but also has gone beyond its core business of making shapes to help surface removal operations take place. If you are decreasing the height from 10.1 to 10.0 cm, it is not because this is the only way to get the final shape but because this is the way you have chosen to remove the roughness. If you had chosen electrochemical machining or polishing, you would not have required to increase the height only to decrease it afterward [10]. Therefore, this height change is not the same one that is required to get the core dimension when the core dimension is not obtained by AM alone.

52 **R2**: What if a size change by post-processing is always considered to facilitate HAM? Will it not simplify the concept of post-processing?

53 **R1**: No, it will cause inconsistency. Let us consider our last example. The cylinder needs to be post-process machined to decrease its surface roughness; therefore, its height was first increased. This is case 1. Again, let us consider a cylinder needs to be post-process electro-machined to decrease its surface roughness; therefore, its height was not planned to be increased. This is case 2. Case 1 becomes HAM because the height was decreased. Case 2 is still AM because the height remains unchanged. Case 1 shows AM does not make a shape; therefore, the final process is HAM. Case 2 shows AM makes a shape; therefore, the final process is not HAM.

Though AM has the same shaping ability in both cases, we get a conclusion that AM does not have the same ability—an inconsistency. The reason: we do not want to know why post-processing is used; we only want to know what it does. If we had known that in case 1, our choice of post-processing—rather than AM—was the problem, then we might not be blaming AM.

54 **R2**: But you are assuming the post-processing is perfect. What if it changes the dimension by error? For example, some surfaces of the part get damaged during sandblasting [11]. Will it come under HAM or AM?

55 **R1**: It comes under AM. We are talking about those dimensional changes that happen when post-processing is used as a strategy.

56 **R2**: Let us consider I use interlayer machining. What will be its effect on the final process?

57 **R1**: It depends on what you do with interlayer machining. If it is used to fine-finish after some layers, it is not HAM. If it is used to change the shape, it is HAM.

58 **R2**: What do you mean?

59 **R1**: Let us consider DED is supposed to print a layer of the right thickness. If it does not print, and machining is used to trim the layer to the right size, then the shaping is done by both DED and machining. In this case, the process is HAM.

60 **R2**: Can you give an example?

61 **R1**: Suppose you want to improve forming accuracy [12]. Suppose after printing some layers, the surface is non-planar, oblique, wave-like, etc. For example, the surface has a wave profile of amplitude 50 μm. Therefore, you want to eliminate troughs and crests to make the surface planar. You use interlayer machining to remove 100 μm. This is HAM.

62 **R2**: If I remove 50 μm because the problem was surface roughness or 100 μm because the surface was nonplanar. In both cases, I rely on interlayer machining to do exactly the same thing. Why is the former not HAM while the latter is HAM?

63 **R1**: In the former, you use machining to get a fine finish. If you do not, you still get the right shape by DED. In the latter, you have a problem getting the right shape. If you do not, DED cannot provide the right shape. Since AM alone provides the right shape in the former case, it is not HAM. While in the latter, AM alone is not sufficient to provide, making it HAM.

64 **R2**: What does it matter? AM should be independent. In the former case, it cannot provide the finish; consequently, it relies on machining. In the latter case, it cannot provide the right shape, and it relies on the machining. In both cases, it has demerits that need to be overcome with the help of something else. Therefore, both cases are the same. I might be calling the former, not HAM, only if AM had provided all properties that a part requires. Is finishing not important, while shaping is?

65 **R1**: AM is a shaping technique [13]; it is not a shaping-cum-finishing technique. Therefore, what matters is what has happened to the shaping, not the finishing. If AM cannot do shaping alone, it is a partial shaping or semi-shaping technique. If a part has the right shape but not the right property, it is still an AM part. If a part has an excellent property, but its shape is finalized by some other techniques, the final part is a HAM part. The excellent property does not compensate for the lack of the shaping ability of AM.

66 **R2**: I understand what you say, but I do not agree.

67 **R1**: Why?

68 **R2**: It is in conflict with the practice.

69 **R1**: How?

70 **R2**: In a workshop, post-processing is considered a minor job. It consists of drilling, painting, roughing, trimming, cutting, cleaning, etc. It is not differentiated on the basis of its effect on shaping. Its status as a minor job remains unchanged as long as its contribution is minor irrespective of its type. For example, both a drilling operation used to make a slot and a trimming operation used to remove stair steps are minor jobs. Therefore, both are identical. They do not change the status quo of an AM part. A drilled AM part will not be called a HAM part because it is minutely different from a trimmed AM part. Do you not see how your reasoning conflicts with the workshop practice?

71 **R1**: Are you saying the reasoning should not be given because it is in conflict?

72 **R2**: What is its advantage?

73 **R1**: There is a clear boundary between an AM part and a HAM part even if the workshop practice blurs it.

74 **R2**: This is a clarification. Is it the advantage?

75 **R1**: Yes.

76 **R2**: Can I ask a practical question about interlayer machining?

77 **R1**: Yes.

78 **R2**: Using interlayer machining, if I remove 50 μm because of the surface roughness or 100 μm because of the nonplanar surface, how will you know why I have removed the material when the effects of both are the same?

79 **R1**: If you remove 50 μm after twenty layers or fifty layers and shall claim that you have removed it because of the surface roughness problem, I shall doubt your intention. Because if you want to remove only surface roughness, you will remove it after the last layer when you finish building your part. It is the roughness of the top surface that gives a fine finish. Besides, the roughness of an intermediate layer is not an obstacle to depositing further layers on it. Therefore, even if you do not inform me, I shall know your inability to print a planar layer.

80 **R2**: Does it mean finishing an intermediate layer is never required?

81 **R1**: It is required when some sections of an intermediate layer are the top layer of your geometry. Then, interlayer machining saves us from the difficulty of accessing the intermediate layer from the top layer.

82 **R2**: Can you give an example?

83 **R1**: Suppose we are making a hollow truncated cone on a cube. Our intermediate layer is the top surface of the cube, while the top layer is the final layer of the cone. If we forget to do interlayer machining to give a fine finish to the top surface of the cube, we need to do machining afterward. Then, the machining tool needs to access the top surface of the cube through the outlet of the cone. Our difficulty will increase if the cone is tall or the outlet is small. The tool needs to maneuvre to avoid colliding with the oblique wall of the cone. We may not get the same surface finish that we can obtain with interlayer machining.

84 **R2**: If I use AM and interlayer machining and the combined process is still called AM because interlayer machining has not changed the shape, how is it different from AM that does not use interlayer machining? Are you not ignoring the incorporation of interlayer machining in AM?

85 **R1**: Since the standard AM does not have interlayer milling, our common sense misguides us into thinking it (AM plus interlayer milling) must not be AM because machining is used—as if machining itself were a red flag. If the machining is unable to change the shape, it is not different from other processes, e.g., interlayer heating used in laser powder bed fusion (PBF) [14], that does not change the shape. It is also not different from interlayer dwell time, which also does not change the shape [15]. If this machining should be considered differently because it is in the form of interlayer processing, note that the interlayer heating comes in the form of interlayer scanning and is not considered differently. We also do not consider interlayer dwell time differently.

Consider PBF and not interlayer heating—the first case. Again, consider PBF and interlayer heating—the second case. How do we distinguish between these two cases? Do we say that the first case is AM, while the second is not AM because it is a combined process of AM and interlayer heating? We are used to using both as AM. If it is required, we can specify that the second case has a process step that is interlayer heating. We do not face the dilemma of why the second one is not considered HAM. But the moment interlayer heating is changed to interlayer machining, we do not apply the same logic. We do not consider the interlayer machining a process step of AM.

86 **R2**: You are missing the point that interlayer machining is not only a removal technique but also used for improving mechanical properties [16].

87 **R1**: We see whether the machining has contributed to the final shape.

88 **R2**: If I use interlayer rolling [17-18]. What will be its effect on the final process?

89 **R1**: It depends on what you do with interlayer rolling. If it is used to change the shape, it is HAM. Otherwise, it is not HAM.

90 **R2**: Is it not the same type of answer you gave when I asked about interlayer machining?

91 **R1**: Yes.

92 **R2**: Do you know the interlayer rolling provides excellent properties that cannot be obtained with post-process rolling [19-20]?

93 **R1**: To find HAM, we see its contribution to the shaping.

Dialogue 2

Shaping

94 **R2**: What do you mean by shaping?

95 **R1**: To create a 3D object, not a 2D or 1D entity. Shape means a form. Shaping means processing a material so it will acquire a form. For example, hammering a flat metal so it bends and takes the shape of a tool.

96 **R2**: But when you talk about a cylinder, its aspect ratio, size, etc., then I get an impression that shape means a geometrical shape. Now you are saying it is a form. Why do you not say a shape is what we understand it to be in geometry?

97 **R1**: I cannot. In geometry, two cylinders of the same aspect ratio are of the same shape. In manufacturing, they are of the same shape geometrically, but they are different minutely. They can have different tolerance, finishes, or cylindricity. For example, if one cylinder is of mm scale and the other is of metre scale. They will not be exactly the same.

98 **R2**: What if they are exactly the same?

99 **R1**: Even then manufacturing techniques and setups will not be the same.

100 **R2**: What if the techniques and setups are the same because they are not much different dimensionally?

101 **R1**: Even then they will be different because they will not consume the same amount of material and efforts.

102 **R2**: You say AM is a shaping technique. Where is it written?

103 **R1**: It is mentioned in the definition – 3D model data is required [21] to start the process.

104 **R2**: Can a part not be made without 3D model data?

105 **R1**: A part can be made [22]. But how it can be made is not equal to how it is meant to be made. If you agree with how it is meant to be made, I mean using 3D model data, you should also agree that AM is a shaping technique.

106 **R2**: What about the definition of other techniques? Do they not need 3D model data?

107 **R1**: There is a difference.

108 **R2**: Can you explain?

109 **R1**: Let us take an example of simple machining. It can be defined as an action that removes material. To define it, there is no need to use 3D model data because the definition does not depend upon what happens—which form it takes—after removal of materials. The removal of materials is sufficient to fulfil the definition of simple machining. Let us compare it with AM. If we add two materials, it is not AM. But if we remove some material, it is simple machining. If we take two layers and add them layer upon layer, it is not AM. But if we divide a block into two small blocks, it is simple machining. If we analyse these examples, we find it is not the action that defines AM, but a particular type of expectation from the action that defines AM. In simple machining, we do not need to go beyond checking the removal of materials to further check the consequence of the removal on the final part. We do not go so far. The definition of simple machining is independent of what happens to the part in a long run.

AM does not have such freedom: we cannot say we have added some layers or we have added the layers in a layer-upon-layer method; therefore, we need not be aware of what form this addition will lead to. We cannot say this, because the definition of AM is tied to 3D model data—it is related to a purpose. The purpose says AM is not only an action, as simple machining is. The purpose makes AM a shaping technique, while the absence of such purpose in the definition of simple machining does not restrict it to a shaping technique. A geometrical shape can be created by simple machining, but this ability of simple machining does not make it a technique only for creating a geometrical shape. A geometrical shape cannot be created by AM, but this lack of ability of AM does not make it a technique for simple joining. While simple machining is a technique for both creating shapes and not creating shapes, AM is exclusively a shaping technique.

110 **R2**: What is ‘purpose’?

111 **R1**: AM has a plan. It has a blueprint. This is the purpose. The action in AM is part of this plan or blueprint. You cannot isolate the action from the plan and say this action is AM. You cannot simplify by saying the action is AM and AM is the action. If you try to call the action AM, you will be questioned whether you are not aware of the history of manufacturing. The action has never been nameless. The action is called by different names, such as adding, joining, layer joining, coating, and cladding. If you insist on equating the action to AM, you will be asked, for instance, ‘Do you mean coating is AM?’

In simple machining, a plan or a blueprint is not required to know what it is. It does not mean the simple machining is a misfit with a plan or is not good enough that a plan cannot be accomplished with it. It only means simple machining does not need to be part of a plan to know what will happen when simple machining is applied to a block.

112 **R2**: Is machining not a shaping technique [23]?

113 **R1**: The ability to define or know, in a minimum way, either simple machining or CNC machining does not depend upon whether it is a shaping technique or not. For AM, there is no equivalent minimum way to define it—when AM is thought to have been deprived of its ability to do shaping, there is no AM left. That is why AM is attached to 3D model data.

114 **R2**: But you say 3D model data is not necessary for AM?

115 **R1**: AM is to make a shape. How you make it does not matter as long as you have not forgotten that it is for making a shape. When I say AM is tied to 3D model data, I mean AM is tied to a shape. When I say 3D model data is not necessary, I mean you can still create a shape even when you do not have resources to make a CAD file, simulation, or automation. I mean doing it manually. I have never meant that an absence of 3D model data means an absence of intention to create a shape. I do not mean when I say 3D model data is not necessary that you occasionally get reprieve from considering what AM should be.

116 **R2**: Can I ask a logical question?

117 **R1**: Yes.

118 **R2**: Let us recall machining. When machining is done on a block, we go and see the block afterward. When we see, we see a change in the block. This change is a change in shape. If there is no change, no machining has taken place. Therefore, if you apply simple machining to a block just once so the block gets a scratch, is it not shaping? Since the scratch is small, will you not consider it a shape-changer? How can machining be known if its effect is not observed in how it changes the shape on a block? I mean, does machining actually happen when you observe the block afterward and find no change? Is 3D model data only for a complex shape?

119 **R1**: How many times have you gone to a workshop, and after scratching with some tools, you have exclaimed, not necessarily with joy, that you have created a shape—that you have created a part? What is the present manufacturing practice? Does a scratch qualify to be called a shape?

Dialogue 3

Comparison

120 **R2**: Does AM prefer a complex shape?

121 **R1**: Yes, it does.

122 **R2**: Is it in the definition?

123 **R1**: No. It is in the practice [24-25].

124 **R2**: Can you give an example?

125 **R1**: Have you not heard "complexity for free" [26-27]?

126 **R2**: It only says a complex shape can be made economically.

127 **R1**: Mentioning a particular type of shape indicates the preference.

128 **R2**: What about conventional manufacturing (CM)?

129 **R1**: They do not have such a preference.

130 **R2**: Why?

131 **R1**: When they make a complex part, it does not give them a benefit to make the next complex part.

132 **R2**: Are you saying there is no such advantage to making the next complex part in CM? Is this why they do not prefer complex shapes?

133 **R1**: You are distorting my statement. What I am saying is AM has an advantage to make the next complex part. This advantage is not found in CM. This advantage shows why AM is different from CM. This lack of advantage in CM demonstrates why a preference in AM cannot be applied to CM.

134 **R2**: What happens in AM?

135 **R1**: In AM, if you have converted a complex design into a part, it is easier for you to make the second part using the last design but with a slightly changed dimension. To make the second part, you have less difficulty. This is the benefit.

136 **R2**: Why 'slightly'?

137 **R1**: I am not talking about extreme dimension changes, i.e., making a micro- or meter-scale part, because they will bring another level of complexity, and the same system will not be enough [28].

138 **R2**: Can you give an example?

139 **R1**: If a complex engine part is made, it is not difficult to scale its dimensions by some centimetres and make another part [29]. Let us call the first part made Part 1 and the part made thereafter Part 2.

To make Part 1, there is no experience available. The only thing present is its design, and there are challenges to overcome. One has to find whether the design can be made with available resources, i.e., whether a particular AM technique is available; if yes, whether a particular system is available; and if yes, whether the lab or workshop has the history to work with similar designs. One needs to find parameters that work. For this, the parameters have to go under trials for different regions or features of the design. If there are more micro features present in the design at a certain height from the substrate, more optimization at that height is required. Materials can be an issue. If permitted, the materials need to be tuned by adding some other material to allow difficult features to be completed. This is the first part that goes through these challenges. If these are solved, Part 1 is ready.

When Part 2 is to be made, the experience is available, which says everything. It says primarily that the complexity is no longer an issue, because it has been solved. Material is available – one does not need to add various combinations of their components to find the right material. Parameters have already gone through process control, and they are proven to work. Simulation is over. Design orientation in the system is known. The issue of a support structure (SS) and an overhang, if any, is solved. This is what we call gaining the know-how. This leads to serial production [30-32].

Though with a change in dimension, everything that is required to make Part 2 will not be the same, but one does not have to start from a zero level. The know-how reduces our difficulty significantly.

140 **R2**: Do you mean an increase in dimension does not increase the difficulty?

141 **R1**: It will require more materials and machine time – this is the difficulty.

142 **R2**: This is not a difficulty. What if adding more layers increases the heat content, which changes the microstructure and properties? What if adding more layers cause a collapse in the sensitive features, for which an additional SS is required? What if a bigger machine or a new simulation is required? What if decreasing layers means decreasing the resolution of small features? What about porosity and anisotropy problems [33-34]?

143 **R1**: I am not talking about all cases. I am talking about the majority of them.

144 **R2**: Can you compare with CM?

145 **R1**: Let us consider injection moulding. If I want to make Part-1, I must first arrange a mould. If I want to make Part-2, I must first arrange a mould. Do you notice what I am repeating? The knowledge that I gained for making Part-1, i.e., experimental parameter optimizations, selection of materials, knowing how materials behave in a given temperature and humidity, shrinkage of the material inside the mould, where the shrinkage happens, offset in the design for the shrinkage, various changes in the design, etc., does not help much. This massive knowledge does not prevent us from again investing my resources in a new mould—this is a major chunk of my difficulty [35]. My difficulty is not reduced. The application of know-how gives some relief but is not able to offset the difficulty that arises due to the requirement of a new mould.

146 **R2**: In injection moulding, there is not a single part, i.e., Part 1. Part 1 is made along with thousands of other part 1s. The difficulty is not reduced from Part 1 to Part 2 because they are not representing a single part. Your assumption was made on the premise that 'know-how' does not reduce the difficulty in injection moulding. The difficulty was not reduced not because your premise holds good but because many parts are also made by default.

Please divide difficulty by the number of parts and prove why you are right.

147 **R1**: In that way, even if I am proved wrong, it will not help.

148 **R2**: Why?

149 **R1**: In injection moulding, a part is never made, but many parts are made, as you have said. Therefore, if I make a single part using AM and want to compare it with a single part made by injection moulding, I am forced to have many parts made to facilitate the comparison. I cannot bypass the requirement of a mould. I do not have a shortcut. Mould is the difficulty.

150 **R2**: Please make a thousand identical parts using AM and choose one, and then compare it with one of the thousand injection moulding parts.

151 **R1**: Are you not aware AM is not used for mass production? It leads to environmental issues [36].

152 **R2**: Are you not aware AM can be used for mass production [37]?

153 **R1**: This is the problem. You are not accepting what AM is for. You are expecting it to do what CM does.

154 **R2**: You are not understanding the limitation of injection moulding. Why do you not compare it with CNC machining?

155 **R1**: Machining works on the basis of the movement of tools. If I want to change dimension, I have to see how it affects the movement. If I want to cut bigger this time, I need to check whether the spindle collides with the workpiece. I need to again work on collision avoidance.

Let us compare with a nozzle-based AM. The nozzle only goes upwards; therefore, it has no chance to collide with an ongoing structure. The collision can only happen when it hits the ceiling of the machine if we have increased the dimension beyond the limit.

CNC machining may require new clamps and fixtures with a dimension change, depending on the complexity. Assuming that no new fixtures are required, even then new tool paths are required, which takes significant time. In AM, a new software program is generated by scaling down or up the existing program [38]. Therefore, with a dimension change, CNC machining requires significantly more software time than that in AM. Although it poses less difficulty than injection moulding with a dimension change, it still poses more difficulty than AM.

156 **R2**: What about a bed-based AM?

157 **R1**: In PBF, a scraper is the only machine part that moves inside the building zone of the chamber. It moves only when the layer is not consolidated. It moves before and after the consolidation of the layer. Therefore, its movement does not interfere with the formation of a part. If the layer is not consolidated well, causing the unfinished layer to protrude out of the surface level, it can collide with the scraper when it moves to spread the next layer. However, if it is assumed that a complex shape is transformed into a part, it is also assumed that any issue of under-transformation is over. Therefore, when a new part is formed only with a change in the dimension, there is no chance for such collision. This is in contrast with machining, where a dimensional change may create a new issue of tool collisions with an unfinished part.

158 **R2**: If a dimensional change means a decrease in the dimension, it may cause a problem in PBF but not in machining. For example, if we decrease the dimension, a cavity becomes narrow. It can still be made in machining

if we change to a narrow drilling tool. It is the problem of the tool to make the cavity. When the tool comes out, the cavity is made. In PBF, when the cavity becomes narrow and powder gets attached to the internal wall of the cavity, nothing more can be done. If we compare, machining has less difficulty after the dimensional change.

159 **R1**: I disagree. If the dimension decreases, it may cause problems in machining but not in PBF. For example, if we decrease the dimension, a wall becomes thinner. It can still be made in PBF; the only problem is that the wall will not have uniform thickness. Therefore, AM is better than machining when we want to make next complex parts with a slight dimensional change.

160 **R2**: What about comparison with forging?

161 **R1**: Let us consider forging. It is used for mass production but is also used for a one-off part. Let us make one part and change the dimension and make another part. The design must be simple, so we do not need another die for Part 2. Let us consider a die consisting of two rectangular blocks. A part is made by pressing sheet metal between the blocks, forcing the sheet to take the shape of the cavity.

When we want to scale up the dimension, we can increase the gap between the two blocks. Let us make Part 1 and again a bigger part, i.e., Part 2, by increasing the gap. Part 1 is simple; therefore, the transfer of know-how is not the information that we are waiting to apply to make Part 2. The know-how will not decrease the difficulty because there is no such difficulty in knowing how to make Part 2. The entire difficulty is how to get an extra dimension by pressing the sheet metal. The difficulty is not reduced simply because we know how to make Part 1. Therefore, there is no difficulty reduction.

162 **R2**: You are considering a simple forging part. Why not a complex one?

163 **R1**: Because another die will be required, which will increase the difficulty more.

164 **R2**: Your premise depends upon making only complex AM parts. You have made a complex AM part and compared it with a simple forging part. Is it fair?

165 **R1**: What is the problem?

Dialogue 4

Simple Parts

166 **R2**: If you make a simple AM part, there is no such value in transferring know-how from AM Part-1 to AM Part-2 as well, which will invalidate your premise. Please make a simple AM part to compare with a simple forging part.

167 **R1**: Why should I make? AM is for complexity. It is used to make mostly complex products [39].

168 **R2**: The complexity has become a weapon for you. Whenever you want to beat other techniques, you are eager to wield it. The comparison between AM and CM should happen on equal footing. It is like you are asked to compare two residential buildings, and you are not taking into consideration all factors, i.e., architecture, strength, windows, doors, water supply, air ducts, etc.; you are choosing only the roof of your building because your roof is stronger.

169 **R1**: You have mistaken AM as a technique that is supposed to make all designs. It is not supposed to make a simple design because other techniques are available for this task.

170 **R2**: What has AM to do with other techniques?

171 **R1**: AM is not an isolated enterprise. It is part of broader manufacturing. It is meant to complement what other techniques cannot do. If others can do this task better, others must be preferred. That is why I talk about complexity. It is not that when simple AM parts are made, AM does not give an advantage. But it should be used for what it is meant for.

172 **R2**: If simple AM parts give advantages, why should they not be used? Your statement is contradictory. Why do you not just say that making simple parts is not an advantageous application of AM; therefore, AM must not be used for simple parts?

173 **R1**: The advantage of making simple parts is nothing but illusion, because it creates confusion over what an advantage should be.

174 **R2**: How?

175 **R1**: Simple parts are made at the expense of trying to make complex parts.

176 **R2**: Can you give an example?

177 **R1**: Let us compare two imaginary AM techniques named A and B. If I want to know which one is better, I shall bring a complex design, i.e., a benchmark, to check the performance of both techniques. The technique that converts the benchmark better will be a better one. Let us imagine A is better. B loses because it could not make it.

But wait for a while. This is not the end of the story. This is the beginning. B lost because it has no desire to compete. Its specialty is not complexity. It only wants to make simple parts, which gives several advantages over A. B does not need process control to check whether optimized parameters work for both micro and macro features of a given design because it does not have different types of features. It makes B free from the control machinery. If B has to make simple parts for a simple purpose, it does not have a critical need for resolution. Then it does not need the layer of machinery required to make a precision part. If the property requirement is not stringent, it does not need machinery to control temperature, depending on the materials. Thus, B does not require as much machinery as A does. Therefore, when both techniques are out to miniaturize their systems, it is B that wins if funding is not exceptional for A.

178 **R2**: Is there a miniaturized B system to make only simple parts, but no miniaturized A system?

179 **R1**: Yes.

180 **R2**: I do not care why and how the miniaturized system is developed. It is not my concern if it is difficult to develop [40]. I can carry it and go to a deep forest. There I shall make simple parts. Is it not an advantage? Is it illusion?

181 **R1**: Let me call this advantage an illusion. It is not because I am so ungrateful that I am not ready to acknowledge it as an advantage. It is because it creates illusion. It says even if AM makes simple parts, it is a technical victory over CM. It is wrong because a competition happens when both techniques are present to compete. In the deep forest, only AM is present. If AM wins, it is not because it makes a simple part better than CM but because the latter techniques are not present to show their competence. AM does not have an expertise developed to make the simple part better. Although the contribution in the deep forest should be appreciated, this appreciation must be different. This is a logistical or strategic appreciation. This can also be called a strategic or logistical advantage. The problem is that we want to present this logistical advantage as a main technical advantage.

182 **R2**: What will be its consequence?

183 **R1**: It gives a wrong impression that the portfolio of AM contains both complex and simple parts. It propagates a false belief that if AM can make a complex part with technical marvel, it is suitable to make simple parts with equally technical marvel.

184 **R2**: If I can use AM in a deep forest where other techniques are not available, it is itself a technical triumph of AM over other techniques. I do not care if the part is not complex enough. How can you say it is not a technical but logistical advantage?

185 **R1**: The layer-by-layer technique is supposed to simplify the manufacturing of a complex design and provide a better alternative over CM. If it provides, it is a technical triumph over the CM. Simplification of a complex design happens only if the design is complex enough to create a scope for the simplification. When a design is simple, there is no scope for the simplification to occur. If AM does not simplify because there is no scope for that, AM is not doing what it is supposed to do. If it is not doing what it is supposed to do, it is not competing with CM, resulting in neither a loss nor a triumph.

In other words, if a singer is singing, he is taking part in a singing competition. If he is only speaking, he is not taking part. But we are so much mesmerized by his voice that even if he speaks, we consider it part of his singing.

186 **R2**: Even if it is a logistical advantage, it is an advantage. What is the cause of the advantage?

187 **R1**: When we select a complex design, we provide a scope for the layer-by-layer method to be exploited. When we select a simple design, we do not provide such a scope. But whatever the design we select, we provide a scope for the method to work. We are not free from the working of the method whether the working leads to simplification of the design or not. If it leads, it matches with the focus of AM. If it does not, the method is still present. The method is itself a simplification of manufacturing, which gives the flexibility to make. When we apply the method to a simple design, it is a victory of the method, but not a victory of the purpose of the method. When we apply it to a complex design, it is the victory of both the method and its purpose.

In a deep forest, you have the method but not the competency to apply it to a complex design. If you cannot apply, you are not in a race to win. Therefore, you do not have any technical triumph there. But you can make simple parts, which is not a technical victory due to the competency but due to the method.

188 **R2**: Are you saying I am using the method but not applying the method?

189 **R1**: Let us consider AM a Mercedes car and CM a hundred-year-old Ford car. When you drive a Mercedes on a highway, it wins the race while a Ford does not. It is the victory of a Mercedes. It is the victory for the reason why it is bought. It does not mean when you drive it in your backyard, it will underperform a Ford. But when you buy it, you do not buy it for the reason you will drive it in your backyard and cherish how much comfort it gives that a Ford does not. In the backyard, if it wins, it is because it is a Mercedes, not because this is what it is supposed to do. In other words, it is not supposed to be driven back and forth there. In the deep forest, if AM wins, it is because AM as a method is better, not because AM as a method is meant to fulfil that purpose.

190 **R2**: You have considered a miniaturized system making only simple parts. Why not a miniaturized system for complex parts? Why are you so negative?

191 **R1**: Are you asking what will happen if everyone becomes a millionaire?

192 **R2**: No, I am asking what will happen if everyone gets cake to eat.

193 **R1**: I am talking about what is happening or possible.

194 **R2**: What is the harm if simple AM parts are made?

195 **R1**: It often creates misunderstandings that cause AM not to be aligned with the goal of manufacturing.

196 **R2**: What is the goal of manufacturing?

197 **R1**: To add value.

198 **R2**: What is the goal of AM?

199 **R1**: To add value.

200 **R2**: Can you give one example of how making a simple part is not aligned with the goal of AM?

201 **R1**: Let us consider I am making a rectangular steel part using PBF. To make it, I need spherical powder within a size range. This specific powder I do not get on its own; I need to process some materials or other powders. This processing is adding value to it. The requirement of this processing is also giving me problems. The moment I decide to convert it into a part using AM, I have selected AM to add value to it. The moment the part is ready, it is time to check how much value is required for the processing to occur and how much value the processing gives afterward. I mean, what is input and what is output? When I compare with other techniques, I realize that I could have got it done more efficiently using other techniques, such as forging, forming, machining, and casting. I realize that the turmoil I have gone through was not worth it.

Let us consider machining. First, we have to find some billet to machine. Finding is not processing. When the billet is available, it does not require having some value added to it to make it fit to be machined. There is no pre-processing stage. When it is machined, it is machined only to separate from the billet. Separation creates the boundary of the rectangular part. The boundary is the only place where machining adds value. However, everything within the boundary is a machined part. The machining tool has not gone anywhere except at the boundary. For example, it has not gone to the centre of the part, but the central area is also called to be made by machining. Let us compare it with AM. Value is first added during the pre-processing stage. Then, it has to start from scratch. It has no choice where not to add value. Every bit of the part goes through processing. A part is called an AM part because there is no area available anywhere in the part that has not gone through processing. Thus, more value is added through AM to get a part that requires less value addition otherwise. Input is more; output is less. This is not aligned with the goal of AM.

202 **R2**: Can you give one example of how making a simple part is aligned with the goal of AM?

203 **R1**: When a steel rectangular part is made using PBF, it is aligned with the goal of AM.

204 **R2**: Just now, you have said it is not aligned.

205 **R1**: I mentioned only one technique, i.e., PBF. If there is only one technique available, we cannot say the value is not added. Conversion of powders into a part—though the part is simple—is the addition of values. After all, the powder is no longer the powder after getting processed by AM. It has become a part. Unless there is a technique, which is AM in this case, that has the efficiency to change it, it will never become a part. Is this efficiency to change not a value addition? AM should be acknowledged that it has successfully added value and accomplished the task. The real show starts when we know that it is not the only technique that can add value. When we have other techniques, we start questioning the worth of this value. When we compare with machining, we realize that this is not what a value should be. Thus, the value changes as the situation changes.

206 **R2**: This type of situation does not exist. This is hypothetical. Is it relatable to real life [41]?

207 **R1**: If you end up in a deep forest with only an AM system to help you out, the situation is no longer a hypothetical one. You are living that hypothetical one. It is not because AM is the only technique available in the world but because it is the only one available to you. You are lucky to have the system, but you are helpless as well, because whatever it offers, you have to accept that happily. At that moment, you might not be questioning the value, but consuming the value.

208 **R2**: Is this the only way relatable?

209 **R1**: Let us consider an example of a medical emergency. A doctor in a hospital needs a spatula during surgery. The spatula is not a part that can be called complex. It is a simple part, purchased in bulk. But when it is not available, it needs to be made within a couple of minutes. AM as a technique can make it within that time frame. AM is available. It is not because other techniques are not available in the hospital or in the vicinity but because their presence does not make a difference. In the deep forest, AM was the only technique available because other techniques were not physically present. In the present case, AM is the only technique available because other techniques cannot make within the window of time. In the deep forest, if it was the space constraint that turned the hypothetical situation into a real one, then presently, it is the time constraint that does.

210 **R2**: You are listing the advantages of simple parts. But your premise is related to complexity. Is not your argument resting on a premise that making a complex shape is difficult?

211 **R1**: It rests on the premise that making a dimensionally changed shape after making a complex shape is easy.

212 **R2**: You start with a complex shape, not with a simple shape. Therefore, you assume that making a complex shape is difficult. Is it not?

213 **R1**: Yes.

214 **R2**: Are you not oversimplifying?

215 **R1**: Why?

216 **R2**: A complex shape is not difficult to make because it is complex but because there is a lack of understanding of the complexity in that shape.

217 **R1**: Can you give an example?

218 **R2**: Consider a structure that resembles an English capital letter 'E.' It consists of a pillar and three arms at its lower, middle, and upper positions. Consider two options. In option 1, we make it without changing the orientation. Therefore, the middle and upper arms need an SS. In option 2, we turn the structure by 90° anticlockwise. This orientation changes the arms into small pillars, removing the need for the SS. Option 1 is more difficult because it requires the SS. Thus, there are two difficulties to making only one shape. Therefore, if we are aware of the reason for complexity, we can decrease the difficulty. Is it not logical to say that complexity, instead of a complex shape, is difficult?

219 **R1**: But still you have to make it. You are not free from making ‘E.’ The shape is complex because it is not 'L,' and it is still difficult because you do not have to make ‘L.’ Therefore, it is more logical to say it is the shape that is complex and difficult.

220 **R2**: If ‘E’ is more complex than ‘L’ and this is the reason why it is more difficult to make, then why do I need to know the complexity?

221 **R1**: If you do not, ‘L’ will be more difficult than ‘E.’ Let us turn ‘L’ clockwise by 90°. You create an overhang by turning. In this orientation, it is more difficult to make ‘L’ because you deal with an overhang. If you compare this with option-2, ‘L’ becomes more difficult.

222 **R2**: There are many shapes for which complexity is not affected by orientation change. Then, why should I know it?

223 **R1**: Knowing it allows selecting a right technique. If you want to avoid making overhangs, it is better to avoid deposition-based techniques, such as Directed Energy Deposition (DED), Material Jetting (MJT), Material Extrusion (MEX), etc., because an SS is always required to make overhangs in these techniques. Otherwise, select bed-based techniques that use powder, such as PBF and Binder Jetting (BJT), where an SS is not required because the bed provides the natural support [42].

224 **R2**: Then, why is an SS made in PBF [43]?

225 **R1**: The bed is not supposed to provide support. It acts as support because it cannot act in a different way. The primary function of the bed is to provide a physical layer that will later become the cross-section of a part. If you want the bed to act as support to any overhang that you make, you must be willing to accept it for what it is. It is made up of loose powder. It is loose because it cannot be packed well. Its packing depends on the movement of a scraper that is used to spread the powder. The movement is generally the only source for packing. The primary function of the movement is not doing the packing but spreading. Therefore, if packing happens, it is the side product of the movement. That is why the bed is not packed well. But the bed should be accepted as it is. It is not because a packed bed is not better than a loose one but because the attempt to improve packing by pressing is counterproductive. The pressing can break fine features under the layer, even if one is willing to accept the fabrication delay caused by employing the pressing.

Therefore, the natural support provided by a bed is what is provided by loose powder. If an overhang is made on loose powder, its undersurface will not have a fine finish. Besides, if the overhang is not light, the loose powder will give in to cause it to bend as well.

226 **R2**: What if I do not want a fine finish, and the overhang of my design is light?

227 **R1**: An SS is no longer a tool to provide only support; it has become a strategy. Suppose you want to make a fine feature and you are afraid that this feature will be knocked down by a scraper when the scraper will come to deposit a layer over it. You are still regretting why the feature is not big. Then, you can construct an SS around it, so the scraper will knock the SS first, saving it from getting directly hit by the scraper.

If you are working on a heat-sensitive material, where heat retained by the material during fabrication is causing problems, such as residual stress, warping, delamination, etc., then you can make an SS to drive away the heat faster [44-45]. A solid SS drive it faster than a porous bed. If you have difficulty in removing a strongly adhered part from a substrate, you can build it instead on a weak SS for its easy removal by cutting through the SS.

228 **R2**: What if my design does not need an SS in any technique?

229 **R1**: Then your design and requirements are simple.

Dialogue 5

Sustainability

230 **R2**: Yes, I want to make a hollow cylinder and do not want a good surface finish. Which technique should I choose?

231 **R1**: You should choose deposition-based techniques, such as DED [46], because it will be fast and does not waste material.

232 **R2**: Are you saying bed-based techniques, such as PBF waste material?

233 **R1**: It can.

234 **R2**: Is it not its demerit?

235 **R1**: No.

236 **R2**: Why?

237 **R1**: Because other techniques also waste.

238 **R2**: Except machining, they waste significantly less [47].

239 **R1**: It is still better.

240 **R2**: Can you give an example?

241 **R1**: In PBF, the amount of material required depends on a design. Let us —

242 **R2**: No, the amount of material depends on the volume of a machine.

243 **R1**: Let me imagine what will happen if a machine is customized to the shape of a part.

244 **R2**: So you are making a small machine for the given shape.

245 **R1**: Yes. Let me figure out its size. The minimum horizontal distance a scraper needs to move is equal to the biggest horizontal cross-section of the design. This is how a layer spread by the scraper will cover the design length-wise. The layer also needs to cover the design width-wise. This is possible only when the minimum width of the scraper must be more than the biggest transverse cross-section. The area covered by the layer provides the rectangular cross-section of a platform required. The minimum depth the platform needs to go down is equal to the height of the design. The area and the height will change with a change in the design orientation. Therefore, we have assumed that we have already found the best orientation, and then we are calculating the area and the height. The volume of material required is the multiplication of the area and the height. This is for the minimum material requirement—a rectangular container full of powder.

246 **R2**: Why rectangular? Why not cylindrical?

247 **R1**: It can be any shape as long as the converted physical part can be submerged in it. It is rectangular because the scraper moves in a straight line. If it moves in a circular line, the container will be cylindrical. But in all cases, it is the outer dimension, not the microfeatures, that decides the container size.

248 **R2**: Am I going to use or waste this amount of material?

249 **R1**: In the best-case scenario, you will have the part and reuse the rest of the material. In the worst-case scenario, you will have the part but cannot reuse the rest of the material; that is a waste. For most of the cases, you will do both, i.e., reuse some material and recycle the remaining one, depending on the material type, design, and your critical requirements.

250 **R2**: So no material is wasted.

251 **R1**: If you cannot use the material as the original one, it is a waste.

252 **R2**: If I recycle it, why is it a waste?

253 **R1**: If it is not a waste, why do you need to recycle it? If you recycle, you do not get the same part property. After some recycling cycles, the materials are not recyclable. They need to be discarded [48-49].

254 **R2**: Let us go back. I know the amount of material depends upon the container size. But why do you mention 'microfeatures'?

255 **R1**: Even if you do not make microfeatures, you need the same amount of material. If material were a currency, you would have already paid in full. It is up to you to decide how to utilize it – whether to make either a complex part full of microfeatures or a simple part.

256 **R2**: Material a currency?

257 **R1**: Let us consider DED. In this technique, material is deposited where it is required. Therefore, you are not wasting the material because you have not deposited it where it is not required. Since you are not wasting the material, no further action is required from you. But in PBF, you might waste the material; therefore, an action is expected from you. The action is in the form of the selection of a design that is complex.

258 **R2**: I understand the problem, but I do not agree with the solution proposed.

259 **R1**: Why?

260 **R2**: Selecting a particular design will not change the history. If I make either a simple or a complex part, the same amount of material is spread.

261 **R1**: If you waste the material in all cases, why do you make a simple part?

262 **R2**: Material is not the only aspect to make a decision. What about energy and time? Are energy and time not important? If a part is complex, we need to figure out how to make it. We need to optimize. All these take time.

263 **R1**: Does the material aspect not give an indication that a complex shape should be preferred?

264 **R2**: The worst-case scenario gives, but the best-case scenario does not. Therefore, there is no clear indication. Making a simple part that saves the remaining material is better than making a complex part that wastes it, which proves a simple one should be preferred.

265 **R1**: What if you consider the time aspect?

266 **R2**: If you consider time to optimize and figure out, simple shapes will take less time. If you consider machine time, complex shapes will take more time. Therefore, there is no clear indication.

267 **R1**: Let me consider the energy aspect and prove why to prefer a complex shape. If you make a solid rectangular part, you have to consolidate everywhere within its outer dimension. If the part of the same dimension is not solid, it is relatively more complex than the solid one. Making the complex one will take less energy because its hollow areas do not need to be consolidated.

268 **R2**: Do you mean if a part is solid, it is simple, and if it is hollow, it is complex?

269 **R1**: Not always. But manufacturing boils down to manufacturing a single layer. If a part starts to become either hollow or complex from solid, the layer starts to become hollow from solid.

270 **R2**: Are you saying that a layer that has become hollow and has only the outer dimension left is the most complex one?

271 **R1**: I am talking about the transition. A layer that is completely solid is simple in design. It is simple not because its consolidation might be easier than a non-solid one but because its consolidation does not lead to a result that cannot be achieved by other techniques easily. Once you have made a solid layer and want to make the next layer that is more complex than this solid one. The only way you can do this is by breaking the status quo of the solidity of the layer. This can be broken by starting to make the next layer hollow. To achieve complexity, you need to check where to hollow.

272 **R2**: I understand what you say. But what was the need to explain? You could have simply said, "When surface-to-volume ratio increases, complexity increases."

273 **R1**: Why? Where is the volume? I am talking about a single layer. If I had to say in terms of ratio, I could have said when the surface-to-bed ratio decreases to a critical value, complexity increases.

274 **R2**: Where is ‘bed’ in non-bed techniques?

275 **R1**: The logic can be applied, considering the bed as an imaginary rectangle that is big enough to inscribe the biggest horizontal cross-section of a design.

276 **R2**: Anyway, let us come back. Your calculation is wrong because you are calculating the consolidation energy only for final parts. You must take into account that you need to make a number of trial parts to make a complex part, while a simple part does not require such trials. If you sum up the energy required for trial parts, it can be more than that for a simple part. It again does not prove that a complex shape should be preferred.

277 **R1**: Trial parts are only for making the first part. If you make the second part --

278 **R2**: Why should I make the second part to support your claim? AM is for one part per design.

279 **R1**: If it is for one part, why trial parts? Why not computer simulation instead?

280 **R2**: To fabrication energy, add computational energy for simulation and mental energy for going through the simulation.

281 **R1**: Do bed-based techniques not prefer complex shapes?

282 **R2**: No. Even if you consider all aspects: time, energy, and material.

283 **R1**: But you have not considered other techniques. A part is not made without considering others.

284 **R2**: Why should I consider? Since PBF can make all parts, I am using this. There must be some reason for me to check other techniques.

285 **R1**: You say PBF is sustainable for both simple and complex parts. This is wrong because sustainability can be known by taking the environmental impact of a technique relative to other techniques.

286 **R2**: So you want to say I must not make simple parts because other techniques are more sustainable.

287 **R1**: Yes.

288 **R2**: But this is wrong.

289 **R1**: Why?

290 **R2**: How do you distinguish between a simple and complex part? If PBF can make both parts, both parts are simple. Is it not? You say a part is complex because it is more difficult to make. But when both are already made, it means none of them are difficult to make.

291 **R1**: This is the reason I am talking about other techniques. If a part cannot be made by other techniques, it is complex for them. If you are making this part, you are making a complex part even if it is simple for PBF.

292 **R2**: I am not refusing to make that complex part. But my problem is why you are not letting me make simple parts as well.

293 **R1**: When you already came to know simple parts are not sustainable in relation to other techniques, why do you want to make them?

294 **R2**: It is not about sustainability; it is about service. I have a PBF machine. If someone wants me to make a simple part, I know it does not fit in a global sustainable vision, but I am still making it to serve the person. Am I wrong? How can I explain to you how much inner peace I get when I serve?

295 **R1**: You are not serving the person. You are serving one technique related to the machine. But service is coming out due to your involvement with the technique. It is not because you intend to serve but because it is the default outcome of the involvement. You could have got more peace if you had recognized the strength of other techniques.

296 **R2**: Do you mean sustainability is more important?

297 **R1**: Yes.

298 **R2**: Which one is more important: sustainability or efficiency?

299 **R1**: Efficiency.

300 **R2**: Why?

301 **R1**: Which one is more important: to have a part accompanied by material and energy loss or to have no part accompanied by no loss?

302 **R2**: Of course, having a part is better. But why are you so negative? Why are you saying we can have a part but no sustainability?

303 **R1**: I am talking about the direction. Efficiency comes first.

304 **R2**: Are you saying we should have the best aircraft even if it accelerates global warming?

305 **R1**: No, I am saying we should not be content with a bullock cart for fear that an aircraft might accelerate global warming.

306 **R2**: Do you mean even if AM wastes material and energy, is it good?

307 **R1**: Only if it makes unique parts.

308 **R2**: If you say times and again that PBF is better even if it wastes material, does it not imply that PBF is designed in such a way that it will always waste the material?

309 **R1**: Yes, it is. All bed-based techniques are designed to be fundamentally unsustainable. The only way we can compensate for the lack of sustainability is by making complex parts. Therefore, making them is not a choice but a compulsion.

310 **R2**: But how are they fundamentally unsustainable?

311 **R1**: Do you not remember how we customized minimum material volume for PBF?

312 **R2**: Yes, but what is unique about it?

313 **R1**: Just visualize how the volume was looking.

314 **R2**: What do you mean?

315 **R1**: Was not it looking like a metallic block ready to be machined? When we do machining, do we not select the smallest block to start with? Will its volume not be the same as the calculated minimum volume?

316 **R2**: So you are saying machining is the counterpart of PBF.

317 **R1**: Yes. The difference is that machining is more aligned with our nature. We are used to converting materials from mines into big blocks, not into powder-sized pieces. We had been doing it for centuries.

318 **R2**: But your logic is wrong.

319 **R1**: Why?

320 **R2**: You have assumed that chips made in machining are equal to the used powder in PBF. You are assuming that both chips and used powder are waste of equal value. Used powder can be reused for the same purpose; chips cannot. Therefore, PBF can be unsustainable, but not for the reason that the used powders are treated in the same way as chips are treated.

321 **R1**: PBF is unsustainable not because the used powder cannot be reused but because it uses powder.

322 **R2**: Do you mean it is unsustainable even if reused powders are utilized?

323 **R1**: Yes.

324 **R2**: But you have just said the best-case scenario and the worst-case scenario, depending upon how the reused powders are used.

325 **R1**: This was when we were not comparing with other techniques.

326 **R2**: But why is it unsustainable?

327 **R1**: Because both—making powder and layer-by-layer consolidation—are unsustainable.

328 **R2**: But why should we use it?

329 **R1**: We should use it like a bitter medicine. Unless we need it, we must not.

330 **R2**: When?

331 **R1**: When we need to make complex or unique parts.

332 **R2**: But minimum material volume is imaginary. Is it not?

333 **R1**: Yes. This is one more thing that we cannot implement. It is far away from the reality.

334 **R2**: Can you explain?

335 **R1**: When we calculate the minimum material requirement, we do not have the means to implement it. We need a customized machine to implement it. We need a platform, scraper, bed, build volume, and internal machine size corresponding to the size of our design. I mean, we need one machine for one design. Otherwise, we need a flexible machine whose size we can change according to the size of our design. And the effort to change is not so much. Otherwise, we will be discouraged and more likely to waste material than to bring such changes. Presently, all machines are bigger. I mean, all designs must be smaller than a machine allows. This results in always wasting more material than one gets from the calculation of the minimum material requirement.

In machining, the size of a workpiece is not tied to the working volume of its system. We are not compelled to always take a workpiece that should be equal to the maximum volume a system allows. We waste material because machining makes chips. We do not waste material because we are compelled to select a workpiece not according to the design but according to the size of the system.

336 **R2**: AM is not only a bed-based technique. What about deposition-based techniques?

337 **R1**: They waste less material and energy. Besides, they cannot make complex parts.

338 **R2**: Should they prefer to make complex parts?

339 **R1**: What does it matter what they prefer?

340 **R2**: Why?

341 **R1**: If they cannot make complex parts, why should it be expected?

342 **R2**: Do you mean they never make it?

343 **R1**: I mean, in comparison to bed-based techniques.

PART 2

Twin-Boundary Framework for AM

Dialogue 6

Framework

344 **R1**: I am developing a framework for AM.

345 **R2**: There are so many frameworks available in AM. What is the need for your framework?

346 **R1**: Can you provide a list?

347 **R2**: The frameworks available deal with various aspects, such as design [50-51], multi-material design [52], assembly [26], production strategy [53], product design [7], implementation [54], functional classification [55], supply chain [56-57], sustainability [58-60], teaching [61-62], management [63], material characterization and process development [64], production planning [65], technology selection [66], standardization [67], big data-based analytics [68], industrial training [69], quality [70], and multi-objective optimization [71].

348 **R1**: None of them deals with the boundary of AM. Therefore, I am proposing a framework consisting of two boundaries:

1. **Boundary 1**: A complex shape is preferred. A shape is complex if it has at least one microfeature and an overhang.

2. **Boundary 2**: Pre-processing, interlayer-processing, and post-processing are not meant to change size and shape. If they change, the resulting process is hybrid AM.

Dialogue 7

Overview

349 **R2**: A framework should have pillars. What are its pillars?

350 **R1**: Two boundaries given are pillars.

351 **R2**: But I could not see a boundary. Where is it?

352 **R1**: Boundary 1 states the boundary between a simple and complex shape, while Boundary 2 states the boundary between AM and HAM.

353 **R2**: If Boundary 1 determines the boundary between two shapes, how can you say this is the boundary of AM?

354 **R1**: This is not the boundary of AM, but within it.

355 **R2**: Are you saying Boundary 1 is about the boundary within AM, while Boundary 2 is about the boundary of AM?

356 **R1**: Yes.

357 **R2**: Are both boundaries not contradictory to each other?

358 **R1**: How?

359 **R2**: Boundary 2 states that post-processing must not change shape and size; otherwise, the process will not be AM. It means the shape should not be complex enough to warrant post-processing. It indicates AM should have a direction from complexity to simplicity to fulfil Boundary 2. However, Boundary 1 states a complex shape is preferred, expecting a direction from simplicity to complexity. Do they both not suggest the opposite direction?

360 **R1**: When Boundary 2 restricts the boundary of post-processing, it expects the boundary of AM should be increased. It means AM should be developed so it can make complex parts without the help of post-processing. The development of AM is the message of Boundary 2. Making an increasing complex shape is its message. This is what the message of Boundary 1 is when it states a complex shape is preferred.

361 **R2**: Is the message not wrong?

362 **R1**: Why?

363 **R2**: The aim should be the development of a product. What does it matter how we make it? In our portfolio, we have many processes, in which AM is one of them. When a problem comes in the form of a complex shape, should we not utilize every resource to solve it? If we ignore the role and quality of other techniques, do we not deprive ourselves of the benefit of these techniques? I am not against the development of an AM process, but I am against it if it leads against the spirit of teamwork. Does the framework fail to accommodate a broad vision?

364 **R1**: When a problem comes, we look for a shortcut. This is why the boundary of post-processing shifts to accommodate our lack of effort. The present framework is needed to clarify the role of post-processing.

Development of a product will not go far without developing a process.

365 **R2**: I am not against your statement that developing a product requires developing a process. But it is not aligned with Boundary 2.

366 **R1**: How?

367 **R2**: Boundary 2 provides a boundary for post-processing. On one side of the boundary, there is AM, while HAM is on another side. The development of a process is not hindered if the boundary is strict or flexible. If the boundary shifts towards AM, HAM is getting developed; if it shifts towards HAM, AM is getting developed. Therefore, the development of a process has nothing to do with the setting up of a boundary. Does it not show the framework's weak foundation?

368 **R1**: It is just like questioning the optimization process in machining. We should be happy in both cases. If machining makes fewer chips, we should be happy that we have saved material. If machining makes more chips, we should be happy that we have more chips to recycle. Is this what you are saying?

369 **R2**: Please explain in terms of the framework.

370 **R1**: It is not similar to selecting the development of one over another but avoiding the problem of AM to shift toward HAM. The boundary is set to prevent one from inadvertently crossing to the HAM side.

371 **R2**: What if one intentionally crosses?

372 **R1**: The framework is only for clarification.

373 **R2**: Why is clarification required?

374 **R1**: To prevent confusion.

375 **R2**: Can you explain?

376 **R1**: Suppose you are developing a method to make a product with the help of AM and post-process machining. You developed a new AM process. You developed a new machine. You made an exotic product. Now, you are presenting these at a conference or tradeshow. People checked the product, knew the details, and returned disappointed.

Seeing your product, people became enthusiastic. They thought you had developed an AM process that is able to make some features that they cannot make. But they found that whenever you found the problem in your product, you used machining to solve it. For you, post-process machining is a means to solve your problem. You are not aware that the post-processing is not meant to change the shape of an AM product. What you presented as a development of an AM process is actually a HAM. Since you do not know that the post-processing in AM is different from the post-processing in HAM, you confused the people. You did not develop a process; you made a new product. What you did was not due to a new process. That was already available. You reinvented the wheel. You were not aware that you were reinventing the wheel, and that is why you presented.

377 **R2**: Are you saying one needs to be aware of the framework to avoid getting problems?

378 **R1**: One needs to be aware of the process development.

379 **R2**: What is the need for the framework for those who are aware of the process development, AM, HAM, etc.?

380 **R1**: The framework is not essential to know all these concepts. It emphasizes the boundary, which was missing.

381 **R2**: I am a hobbyist as well. I have a material extrusion or fused deposition modeling system [72-73]. Should I first check the complexity of a part before trying to make it? What is the role of the framework for me?

382 **R1**: The framework has no direct role to play for you. The framework is about the process definition, geometric preservation, limitations of a technique, effect of crossing the limitations—these are related to the policy, scope of a subject, expectation from an industry, etc.

Dialogue 8

Boundary 1

383 **R2**: In the first part of Boundary 1, why do you say a complex shape is preferred?

384 **R1**: Because the specialty of AM is complexity.

385 **R2**: Is the foundation of the first part of Boundary 1 not wrong?

386 **R1**: Why?

387 **R2**: A technique is meant to solve all problems that it can. If it is restricted only to complex shapes, the advantage obtained from applying it to simple shapes will be lost.

388 **R1**: Can you give an example?

389 **R2**: Have you not heard about on-demand production, making an emergency part or a few parts without making moulds? These are not necessarily complex parts, but they are drivers for growth, business, and service [74]. Do you want to say these advantages are not worthy?

390 **R1**: What I mean is that a complex shape is preferred, not that it is the only shape that should be allowed.

391 **R2**: Are you saying these simple parts should be made?

392 **R1**: Yes.

393 **R2**: Then your statement is not clear.

394 **R1**: Let me give you an example. Suppose you make a metallic sheet using PBF. It is a simple part, and if you still use AM, it is against sustainability. You must use machining instead. Machining is more efficient to give you a sheet by separating it from a big sheet. If you are avoiding machining, you are not acknowledging the efficiency of machining. If you still want to use AM, you want to show AM as a dominant force that can do everything alone. AM should be a team player—this is what the first part of Boundary 1 wants to convey.

395 **R2**: If you make a simple wire-fed DED part, it is more sustainable [75]. Is a complex part more sustainable than a simple part?

396 **R1**: It is not always true. But, for example, if you make a mould using PBF, it is more sustainable than making a metallic sheet.

397 **R2**: Last time, you said AM should be developed to acquire a capability for making complex parts. Now, you are talking about how AM should be more sustainable. Are not they unrelated goals?

398 **R1**: It is better to have a complex part that is sustainable than one that is not sustainable. But it is not better to have a mass production of simple AM parts even if it is sustainable. Because for making such simple parts, other techniques are available. Boundary 1 wants to convey that it is better to develop other techniques for sustainable simple parts than to employ AM.

399 **R2**: How do you distinguish between a simple and complex shape [76]?

400 **R1**: This is generally avoided because complexity is relative. What is simple for one technique may be complex for another technique. The geometry that is simple for one material may be complex for other materials, etc. It is easy to distinguish between simple and complex when they are far different. But the problem is on the borderline. For example, primitive shapes—a cube, rectangle, prism, cylinder, etc.—are simple. They can be easily distinguished from a geometry used as a benchmark. These primitive shapes or benchmarks are far away from the border. We need to find some marker that will help distinguish.

401 **R2**: But you try to distinguish it in the second part of Boundary 1. You say a complex shape should have a microfeature and a big overhang. Are you saying microfeatures and overhangs are the markers?

402 **R1**: Yes.

403 **R2**: What is a microfeature?

404 **R1**: A microfeature is a thin pin, narrow hole, thin wall, gap between two features, slot between two sections of a part, etc.

405 **R2**: What is the role of a microfeature?

406 **R1**: Complexity is related to a process. If a process provides 10 μm resolution and you make a part that has less resolution, i.e., 100, 200 μm, etc., the part is not complex enough for the process. If a shape is called complex, it is complex only when a process needs to use its full capability to make it. Therefore, a shape must have a microfeature.

407 **R2**: Can you clarify what a process is? Is it not a set of steps?

408 **R1**: Here, a process means a technique. Since a technique follows a set of steps, a technique is interchangeably called a process.

409 **R2**: Why not a system or machine instead of a process?

410 **R1**: A process has a fixed resolution. For example, stereolithography [77] has a higher resolution than PBF, while it has a lower resolution than two-photon polymerization [78]. If I use "process," I am talking about a general resolution. If I use a machine, the resolution can be different for different models or types.

411 **R2**: You say a process needs to use its full capability. Can you clarify?

412 **R1**: A complex shape should have that size of a microfeature that will match the capability of the process. This is the only way we can know that we are not using that shape that is simple and we are still calling it "complex." It is just like if we want to know the minimum capability of a marathon runner, we will not ask the runner to run only one mile. We must not declare that one mile is the right benchmark to decide whether a runner can run a full marathon.

413 **R2**: In this way, there is no universal size for a microfeature. You are using different complex shapes for different processes.

414 **R1**: The aim is not to find a unique shape that will be complex for every process. We want to know the boundary between a complex shape and a simple shape. The boundary will be different for different processes.

415 **R2**: But the size of a microfeature, even if it is related to the resolution, cannot decide the boundary.

416 **R1**: Why?

417 **R2**: Because the resolution provides negative information, not positive information.

418 **R1**: How?

419 **R2**: If the resolution is 50 μm, it implies that a microfeature less than 50 μm cannot be made—negative information. It informs that a microfeature more than 50 μm cannot always be made—somewhat positive information. The negative information is guaranteed. If a thin wall of thickness 50 μm and height 5 mm is made, it does not give a guarantee that you can increase its height to 10 cm. Fabrication of a microfeature is related to its complete dimension [79]. Even if it is made, there is no guarantee that it, if tilted by 20°, can be made. Therefore, unless you specify a microfeature, there will be many boundaries between a simple and a complex shape.

420 **R1**: The microfeature that can be made with minimum effort is the boundary. For 50 μm resolution, a wall of thickness 50 μm and a height of even 1 mm are acceptable as a marker for complexity. It does not mean that features that have 5 mm, 10 cm, or more heights are not more complex, but it only means the feature that is least complex is a marker, while other complex features are not markers. What is of interest is the presence of complexity, not its degree. What is of interest is where a boundary is, not how big regions are on both sides of the boundary.

421 **R2**: I do not doubt the clarity of your intention. I doubt its practicality.

422 **R1**: Why?

423 **R2**: For the same resolution, as per your framework, a wall of thickness 100 μm and 10 cm height is a simple feature, while a wall of thickness 50 μm and 1 mm height is complex. Let us make both. It is easy to make the complex feature, while it is difficult to make the simple one. What the framework considers a simple shape is actually a complex one. Therefore, you cannot draw a boundary line without specifying the complete dimension of a microfeature.

424 **R1**: The framework says there must be a microfeature and an overhang. You are only considering a microfeature. Where is your overhang?

425 **R2**: Let us talk about microfeatures. We can ignore the overhang for the time being.

426 **R1**: Today I shall not ignore the overhang.

427 **R2**: No problem. Let us add one overhang to the shape containing these features. Can you clarify where the boundary is?

428 **R1**: There is no boundary. When you added the overhang, both shapes became complex. The framework is not meant to inform which out of two complex shapes is more complex.

429 **R2**: But this is not what was expected from the framework. It is not able to draw a boundary. How can--

430 **R1**: When a boundary is not required, the framework does not provide it.

431 **R2**: But I want to know the concept. Can we partially ignore the overhang for the time being?

432 **R1**: Yes.

433 **R2**: I am making a solid cube with a side of 5 cm. On top of it, I make a feature that is a thin wall of thickness 100 μm, 10 cm height, and 2 cm length. This is a simple feature. I have also added five vertical cooling channels of diameter 500 μm on all four vertical sides of the cube. Thus, there are twenty channels. According to the framework, these channels of such internal big diameters are again simple features because they are neither microfeatures nor overhangs. Let us call this shape cube 1.

Let me make another cube of the same dimension. On top of it at the left corner, I make a feature that is a thin wall of thickness 50 μm, 1 mm height, and 2 cm length. This is a complex feature. On top of the cube at the right corner, let us make a cube with a side of 2.5 cm. Half of this small cube is extended outside the periphery of the big cube. This extension makes this cube an overhang. Let us call this shape cube 2.

According to the framework, cube 1 is simple, while cube 2 is complex. Can you clarify which one is complex?

434 **R1**: Cube 2.

435 **R2**: Why?

436 **R1**: Why not?

437 **R2**: For me, cube 1 is more complex. There are twenty channels to be made, which--

438 **R1**: Twenty channels is an optimization problem. If you solve it, you can make it. Therefore, it is not more complex.

439 **R2**: What if I add two hundred channels?

440 **R1**: If you want, you can add two thousand channels as long as they do not become narrow enough to be classified as microfeatures. Even then, it is an optimization problem. Therefore, it is not more complex.

441 **R2**: What about the overhang? Is it not an optimization problem?

442 **R1**: Besides the optimization problem, it is an SS problem as well. Even if you optimize, you need an SS for many designs [80]. Therefore, it is more complex. For such vertical channels, you do not need an SS. This makes cube 1 not more complex.

443 **R2**: What if optimization for channels is far more difficult than the optimization for the overhang, so making the channels becomes more difficult than making both the overhang and the SS?

444 **R1**: Optimization is a skill problem. If it is difficult for you, it means you are not skilled in optimization.

445 **R2**: What about an SS?

446 **R1**: If an SS is required, you cannot avoid it. You cannot say I have developed more skill; therefore, my skill will replace the SS. A requirement for the SS is tangible evidence that there is a difficulty or complexity that you cannot swap with your skill.

447 **R2**: Are you saying there is no skill required to make an SS?

448 **R1**: When you need an SS, your skill will not free you from this need. I understand you have skill making different types of SS for various complex shapes, but this skill is only for making an SS, not for eliminating its requirement.

449 **R2**: Are you not undermining the difficulty of an optimization problem by classifying it as a skill problem? Why do you not accept that the optimization can take several days, while making an SS takes minutes or hours?

450 **R1**: You are not understanding my problem that I cannot quantify your difficulty, while an SS can be quantified by its presence or absence.

451 **R2**: How can a framework be accepted if it fails to capture the real difficulty?

452 **R1**: Let me clarify that the foundation of the framework is not to quantify such difficulty but to characterize complexity.

453 **R2**: Then why did you try to quantify it? Why are you not straightforward and say the foundation of the framework has nothing to do with such difficulty?

454 **R1**: I quantified it to show why it should not be the foundation of the framework.

455 **R2**: You have until now given me the impression that you are quantifying difficulty. Is an overhang a complex feature but is not difficult to make?

456 **R1**: An overhang is a complex feature because it is difficult to make.

457 **R2**: So you are characterizing complexity on the basis of difficulty.

458 **R1**: Yes.

459 **R2**: You say you are not for quantifying the difficulty but characterizing the complexity. Again, you say the complexity depends on difficulty. Is it not contradictory?

460 **R1**: No.

461 **R2**: Why?

462 **R1**: The framework is about finding a complex shape. Finding it depends on finding complex features. Finding them depends on finding the difficulty in fabricating them. The framework informs that a microfeature and an overhang are each found as a marker to identify a complex shape. Thus, the framework is about finding an initial difficulty, which can be enough to identify complexity.

There can be thousands of shapes that can be more difficult even without having these markers. Since they are difficult, they can be considered complex as well. The framework is not about denying their difficulty or their complexity. The framework is not a benchmark to determine the degree of complexity. Therefore, the framework can exist without denying their complexity, without antagonizing their own notion of complexity. If the framework considers these thousands of shapes simple, it does not mean it is there to prove that they are not complex. It only means these thousands of shapes are outside the framework. You can keep them outside because there is no doubt whether these shapes are simple or complex. The framework is only for those shapes for which there is doubt. The framework has two markers to apply to check whether they are complex or not. The framework answers the question only in the mode of either/or, i.e., go/no go.

463 **R2**: So cube 1 is simple according to the framework.

464 **R1**: Yes.

465 **R2**: But you understand cube 1 may be complex.

466 **R1**: Yes.

467 **R2**: Does not the framework give wrong information when it says a complex shape is simple?

468 **R1**: No, it does not give.

469 **R2**: Why?

470 **R1**: Why do you seek the information from the framework when that information is not required? The framework is only to clear your doubt.

471 **R2**: What if I accept cube 1 is simple because I sought information from the framework?

472 **R1**: What will you do after you accept that it is simple?

473 **R2**: I just wanted to know whether you are willing to accept the consequence of misleading people.

474 **R1**: If you know how you can be misled, the framework is not for you. It is for those who have doubt about a shape. It is for those who are not aware of what AM stands for.

475 **R2**: So the framework will create awareness. Can you suggest how a policymaker who is aware of the framework will make a decision?

476 **R1**: The policymaker will check whether a shape or design given for approval has necessary features. If the shape has those markers, the policymaker knows the design cannot be rejected in the further rounds of approval.

477 **R2**: But the policymaker may be wrong.

478 **R1**: May be.

479 **R2**: Then what is the use of the framework?

480 **R1**: To make the policymaker aware that AM is for making complex shapes.

481 **R2**: Is it important information?

482 **R1**: It can become important.

483 **R2**: When? Can you give an example?

484 **R1**: When mass production of simple AM parts will start because of the policy failure.

485 **R2**: Do you believe a person can become a policymaker without knowing the basics?

486 **R1**: What are basic things?

487 **R2**: A policymaker will know all basics [81].

488 **R1**: If one knows all basic things, one still has to synthesize them to reach a decision. The framework makes one's life easy by saying there is only one basic thing.

489 **R2**: Let me first know the framework well. If I understand well, it uses the markers to find whether a shape is complex or not. But you say a shape can be considered complex even if it does not have markers. If yes, can you explain how the framework gives definitive information?

490 **R1**: It gives definitive information in the sense that it helps identify which shape is complex, but not in the sense that this is the final method to identify a complex shape.

491 **R2**: This is not definitive information. Your method says a shape is simple. The same shape can be proved complex. When it is proved so, you do not become upset. Do you not believe your own method?

492 **R1**: The method given in the framework has purpose. The purpose is to engage stakeholders in the question of the goals and objectives of AM. The moment you say that you reject the markers because they do not capture the complexity, you are rejecting them, but you are still aligned with the goals of AM. By rejecting them, you are still not able to reject the purpose of the framework. Is this not definitive information?

493 **R2**: This is the only one side. You are not talking about the other side.

494 **R1**: What is that?

495 **R2**: What about misapplying the framework? What about faking the engagement? I am rejecting the markers not because I am looking for a solution and have become disappointed with the solution provided by the framework, but because I want to continue with what I am already doing. It means, for instance, if I am engaged in the mass production of simple AM parts, I want to continue doing it. For me, the exercise of rejecting the markers is not an opportunity to engage in a grand debate of the century. Rejecting it is my only aim so it will not disturb my comfort. So it will not disturb my business.

496 **R1**: The framework will catch you soon. Before it, please let me know how you can prove that a rectangular or cylindrical part is complex.

497 **R2**: What do you mean?

498 **R1**: Let us imagine we have a shape without complexity markers. This is a simple shape. This is shape 1. Let us imagine there is another shape. It is complex because it has complexity markers. This is shape 2. As long as shape 1 competes with shape 2, the framework is silent. This silence is the definitive information. This silence gives consent for shape 1 to be considered complex and go ahead with production. When shape 1 is a rectangular or cylindrical part or a combination of such shapes, it cannot compete with shape 2. Can you prove a cube is more complex than an overhang? Can you prove a rectangular part is more complex than a deep slot? You cannot prove it. The markers are playing their role to distinguish between a simple and complex shape. The framework is fulfilling its aim. What is the result? Simple shapes are prevented from getting fabricated. This is tangible evidence of the definitive information. But this definitive information is neither better nor different than the previous definitive information, because both are fulfilling the same aim of the framework, i.e., ensuring the movement from simplicity to complexity.

499 **R2**: To know whether a rectangular part is simple or complex, I do not need any framework. Is it right to use such simple parts for comparison? No one fabricates such rectangular or cylindrical parts using AM these days.

500 **R1**: Parts are produced not because there is a framework to suggest their shapes. They are produced because a need arises somewhere. I know there is no need for such a rectangular part to be made by AM. But I mentioned it. It is not because the framework is robust only for such simple parts but because the framework has applicability. You cannot deny it. You cannot bring any simple parts and also prove them complex. The framework is not that defenceless. You cannot always have a workaround. This is the message this comparison gives.

501 **R2**: Do you want to say the framework suggests how to design a shape, so it will be complex?

502 **R1**: It is not your teacher. It acts as the police. You design. Before you fabricate your design, the framework intervenes. It has two markers to check your design.

503 **R2**: After that?

504 **R1**: Either AM or not AM.

505 **R2**: It is so simple. Is there no use of multi-criteria decision-making or method [82-83]?

506 **R1**: But first you need to know whether AM is for you or not. After that, you can use them [84].

507 **R2**: Can you explain why you have selected an overhang as one of the markers?

508 **R1**: Please suggest another one. It can be a cooling channel, undercut, bridge, lattice, curved surface, internal hollow section, angled surface, angled section, enclosed void, etc. Please provide only one. I am here to simplify. I am not interested in providing a long list.

509 **R2**: Simplification is not possible. You are underestimating the complexity of the subject.

510 **R1**: The subject is complex; therefore, the simplification is required.

511 **R2**: You can miss nuances. Why do you not provide some complexity metrics [85-86]? My suggestion is that you provide metrics using a scale from zero to ten and mark each feature with a specific number according to its complexity. The list will be long, but the details will be appreciated.

512 **R1**: You are not understanding my aim. I am trying to find the cause of complexity. I am looking for a single feature that is special to AM that can help distinguish between a complex and simple shape.

513 **R2**: What is the final aim?

514 **R1**: The aim is to create a traffic light. When the signal is green, you can go. When the signal is red, please stop.

515 **R2**: But you have just said the framework acts like the police.

516 **R1**: This is how the police act.

517 **R2**: That is why you have chosen an overhang.

518 **R1**: Yes.

519 **R2**: Why not a conformal cooling channel [87]?

520 **R1**: Are you saying there is no overhang in a conformal cooling channel?

521 **R2**: What do you mean? Are they not different?

522 **R1**: I am not looking for how much different they are. I am looking for what the common reason or thread is that makes them difficult.

523 **R2**: Can you explain an overhang?

524 **R1**: An overhang means there is no previously built structure underneath to support it. This is the problem. A support is required. But how much support is required depends on how severe a problem the overhang creates. Suppose the overhanging is small. It means the extension of the unsupported layer is small. It is so small that it does not need a support. It is so small that it does not fall. It is not because it is technically not an overhang but because its bond with its own layer is strong. This is one extreme of an overhang where overhanging is not a problem. There is another extreme where it is a problem that requires an SS. Between these two extremes, an overhang creates a range of problems, which is either increasing or decreasing, depending upon from which extreme we observe. At one extreme, material has no risk of falling due to gravity. At another extreme, it has a high risk of falling due to gravity. Between these two extremes---

525 **R2**: But I am surprised when you said there is an overhang in the conformal cooling channel.

526 **R1**: Let me continue. Between these two extremes, materials experience different degrees of gravitational pull. We attach the pull with different types of overhangs. We accept there is a pull, but we do not want to see it without attaching it with the overhang. We are so obsessed with the attachment, we do not want to imagine the existence of the pull independently. We do not want to say that the angled surface is a type of overhang. We do not want to say that a conformal cooling channel, an undercut, or enclosed void is a type of overhang [88-89]. It is not because they are not different. It is not because the subject cannot accommodate the diverse terminology. It is also not because the gravitational pull is such a grand problem that solving it will solve all problems. It is because we cherish the differences so much, we fail to notice the common factor.

527 **R2**: You have mentioned in the framework that the overhang should be big. So you are interested in that overhang that has a high risk of gravitational collapse.

528 **R1**: Yes, so it will not be self-supporting [90-91].

529 **R2**: What next?

530 **R1**: If I make an overhang, I learn how to deal with various risks of gravitational collapse. If an overhang is made by a particular AM technique, it shows that the technique can deal with various risks of gravitational collapse. If a design has an overhang, the design can be used as a test artifact to check the design ability of a technique.

531 **R2**: I understand what you are going to say – the presence of an overhang in a design is a measure of complexity because it can test the ability of a technique. Is it right?

532 **R1**: Yes.

533 **R2**: But where is the common thread?

534 **R1**: The problem in AM is that material falls. It is the common thread.

535 **R2**: Is it not oversimplified? Can you explain?

536 **R1**: If we make a vertical wall, there is no problem because material does not fall. Material remains on the last layer; therefore, it does not fall. The moment we start to tilt the wall, the material cannot remain on the last layer. The problem starts [92]. The more we tilt, the more problems we get. But we do not like to say that material is falling, and therefore, we are getting a problem. We are used to saying that we are getting problems because we are making bridges, angled bridges, curved surfaces, undercuts, overhangs, etc. [50].

Do not say that you cannot make a vertical wall; I am assuming you can make it. Do also not say that you cannot make some microfeatures and the problem is not a material fall, because they are mainly related to the resolution of a process.

537 **R2**: So I shall not always blame the material falling if I cannot make a thin wall or narrow hole in PBF.

538 **R1**: You are right.

539 **R2**: But material does not fall in a bed-based technique because there is a bed. It falls only in a deposition-based technique. How can you generalize it?

540 **R1**: In bed-based techniques, there is a difference when you build a layer on a previously consolidated layer and on a non-consolidated bed. The non-consolidated bed does not provide as strong support as a previously consolidated layer provides. This lack of strong support can be observed when the next consolidated layer bends, sinks, or collapses, depending on the size and geometry of the feature. This problem is due to the material fall. The material of the next consolidated layer does not remain in its place but goes downward due to gravity. This downward trend of the material is sometimes called bending, sinking, or collapsing. Due to the weight of the feature, the material of the bed gets depressed. This depression is the material fall. But this fall is of a lower degree or scale than what happens in a deposition-based technique.

In the deposition-based technique, the next layer is deposited either on a previously consolidated layer or on air. The moment you are about to deposit on air, you know the material can fall; you recognize the problem. You try to find a solution by looking for an SS. The bed-based technique delays you from recognizing it. The bed acts as a proxy. It acts as your false friend, which gives you an illusion of the absence of the problem because of the absence of the air or gap. But the problem is present because it emanates from the layer-by-layer method.

541 **R2**: If the problem is small in bed-based techniques, how can this define AM? Do you mean other problems—such as process control, layer consolidation, and system development—are smaller and therefore deserve less recognition?

542 **R1**: It is not about the magnitude of the problem but about its origin. Let us consider one problem, i.e., layer consolidation to compare and check. It is related to a layer. It is not related to the method. Therefore, if it is solved for a layer, this solution can be transferred to another similar layer. If a vertical rectangular pillar is made, there is no problem in the consolidation of the next layer if the consolidation of the previous layer is solved. But if the pillar is tilted, it is no longer only a known consolidation problem. It is a material falling problem as well, which requires extra optimization. This extra optimization is evidence that material falling is not the problem of a layer but of the method.

543 **R2**: Can you explain why you attribute it to the method?

544 **R1**: The material starts to fall because there is an inherent problem in the method. The problem is that the method is constrained to have only horizontal layers. They are not allowed to tilt. If the bed is allowed to tilt when the pillar tilts, the material will not fall. We cannot solve the problem, because we cannot tilt the bed. The moment we say we have solved the problem. We start to underrecognize the problem—material falling. The solution is to prevent the material from falling. We do not do that. We let the material fall. When the material falls, we manage the consequence of its fall. We call this management a solution. Let us check how we manage it. We bring an SS. It stops the material from falling further. We say we have solved it. But we did not solve it by preventing the material fall from originating. We cannot let it originate because we cannot do away with the horizontality of the bed. If the fall is small and, therefore, the problem is small, then it is easy for it to get unnoticed in the presence of other problems. Even then, it does not change the fact that it is related to the method. Therefore, it defines AM.

545 **R2**: If I optimize for the first layer, I again need to optimize after many layers because of the heat accumulation in certain AM [93-94]. How do you say I need to optimize only if I change the angle of the build?

546 **R1**: Even if you optimize after many layers, it does not help. You again need to optimize if you change the angle.

547 **R2**: Extra optimization is required in both cases. If extra optimization is the reason for which you attribute the problem to the method, then both problems, i.e., the heat accumulation and the angle change, must be ascribed to the method.

548 **R1**: The heat accumulation problem appears after many layers. If it were due to the method, it could have appeared from the second layer. Thus, the first problem may never appear, depending upon the number of layers and the type of the system. However, if the angle change is high, the second problem will appear from the second layer onwards.

549 **R2**: Let us come back. If material falling is the cause, why have you included an overhang as a marker? Why not a conformal cooling channel?

550 **R1**: Because an overhang is easier than the channel to make. My interest is to find a feature that will be near the boundary. If it is difficult, it will be far away from the boundary.

551 **R2**: Why is the overhang easier?

552 **R1**: Because you also need to remove the material from inside the channel [95].

553 **R2**: Then why not an angled feature?

554 **R1**: Then you have to specify the angle. An overhang captures the complexity without needing further explanation.

555 **R2**: But you have already specified by mentioning that it should be big.

556 **R1**: 'Big' means it must be big enough to need an SS.

557 **R2**: But it will not help you, because an SS can be avoided by changing the orientation of a design. Therefore, the design can have an overhang, but not a need to make the SS [96-97].

558 **R1**: Presence of an overhang shows the design is complex enough to be accepted as complex. The requirement of an SS is a signal to identify a feature, i.e., an overhang. If orientation is changed to do away with the requirement, this need to change itself shows why the overhang is complex.

559 **R2**: If it is such a complex feature, why is an additional marker, i.e., a microfeature, required?

560 **R1**: The overhang shows the problem of the method. If your design has an overhang, fabrication of the design shows that the design is complex enough to demand the employment of the method. But this does not show the range of the design capability of the technique. To test the range, you need to have a microfeature.

561 **R2**: If the microfeature can test the full capability of the technique, then why an overhang?

562 **R1**: There are many microfeatures that can be made without an SS [98-99]. Thus, incorporating a microfeature in the design does not show that the design is complex enough to test that capability of the technique that requires the SS. The framework does not give the details of a microfeature. In the absence of such details, there is a need to incorporate an overhang.

563 **R2**: Do you want to say if you have two microfeatures, one of which requires an SS, then there is no need for an overhang?

564 **R1**: It could be sufficient for the reason that two microfeatures can test the capability of a technique. But the framework does not mention the design size. Due to the lack of this information, it will not be clear whether the framework is for a micro design or all designs. Therefore, mentioning the overhang in the framework implies that it is not meant only for micro types.

565 **R2**: You say these markers will test the capability of a technique. I am confused as to whether they are meant to test either a technique or the design complexity.

566 **R1**: We say a design is complex only when it is able to test the design capability of a technique.

567 **R2**: What is the use of those designs that are called complex because they are testing the capability, but in the real world they are considered simple?

568 **R1**: Can you give an example?

569 **R2**: Let us consider a part similar to an English letter ‘E.’ Consider a tiny hole on top of it. This design has both markers. Its upper and middle arms will fulfil the criteria of the second marker, i.e., an overhang. The tiny hole on the upper arm is already fulfilling the criteria of the first marker, i.e., a microfeature. This design by virtue of having both markers is a complex shape. Therefore, it also tests the design capability of an AM technique. But this is not complex, because it can be made by casting easily. In the machining process as well, we can make it and drill a hole on the upper arm.

570 **R1**: The framework is about finding a boundary between a complex and simple shape. In the real world, the shapes that are at the boundary may not be called complex.

571 **R2**: Instead of finding markers to define complexity, why do you not follow a conventional method?

572 **R1**: What is the method?

573 **R2**: Take a 3D design. Imagine a bounding box surrounding the design. Find the volume of the two. Calculate the volume ratio. Imagine a sphere having the same volume as that of your design. Find its surface area. Find the surface area of your design. Calculate the surface ratio using the two. Multiply the surface ratio and volume ratio. Inverse it. It will be the design complexity of 3D design [100].

574 **R1**: How to calculate each ratio?

575 **R2**: Ensure that it is always less than one. Therefore, always divide by a bigger number. Bounding box volume is always more. Therefore, make it a denominator. Sphere area is always smaller. Therefore, make it a numerator.

576 **R1**: According to this method, a sphere is simple. But it is complex to make in AM. If it is big, you cannot make it in deposition-based techniques; in bed-based techniques, you will have surface problems. Therefore, the method does not work.

577 **R2**: Why does it not work?

578 **R1**: It does not take into account the overhanging aspect of the sphere.

579 **R2**: Is a sphere simple or complex according to the framework?

580 **R1**: It is simple.

581 **R2**: Why?

582 **R1**: It does not have the first marker. Having only the second marker, i.e., the overhanging aspect, is not enough.

583 **R2**: If it is simple according to the framework, why do you reject the conventional method by calling it complex?

584 **R1**: The framework considers it simple because it should not be made by AM. The conventional method terms it simple on the basis of its geometry. A method only on the basis of geometry does not work in AM. A sphere that is simple on the basis of geometry is not simple to make in AM. This shows why the method is wrong.

585 **R2**: Why are you not happy that both—the conventional method and the framework—term it the same, i.e., simple?

586 **R1**: Can I ask a simple question?

587 **R2**: Yes.

588 **R1**: Which method do you prefer to make a big metallic sphere: PBF or casting?

589 **R2**: Casting.

590 **R1**: This is the answer to your dilemma. This is what the framework suggests.

591 **R2**: Can you explain?

592 **R1**: The framework considers a sphere simple not because it cannot be made by AM but because it should not be made by AM.

593 **R2**: What if I add a thin wall on top of the sphere? Now, the design has both markers. Please suggest why it should not be made by AM.

594 **R1**: Can I give a personal suggestion?

595 **R2**: No personal suggestion. No opinion. Only according to the framework. You are killing my time.

596 **R1**: Can I speak honestly?

597 **R2**: Be honest or dishonest. But say only what the framework suggests.

598 **R1**: The framework fails.

599 **R2**: It is very sad. Why do you not defend it?

600 **R1**: How?

601 **R2**: Make all techniques fail. Prove why all other techniques fail but AM does not.

602 **R1**: How?

603 **R2**: Make casting fail by saying that the liquid cannot fill the cavity to make a thin wall when simultaneously making the sphere. Make powder metallurgy fail by

saying the mould is expensive to make such a thin wall along with the sphere. Besides, heat optimization for the thin wall along with the sphere is difficult. Make machining fail by saying a lot of chips will be made while making a thin wall on the sphere. Besides, it will take much machining time to make the sphere and the thin wall. Prove why AM is best. Prove why markers never fail.

604 **R1**: I know how to defend it. I can defend it better. But even then the framework fails.

605 **R2**: Why?

606 **R1**: This is not aligned with the goal of the framework.

607 **R2**: How?

608 **R1**: The goal of the framework is not to reject other techniques. Its goal is to reject the misuse of AM. Markers are designed to prevent the misuse. But they are not foolproof. Being not foolproof does not mean they are weak. It only means even if they are strong, they will not work in all cases.

609 **R2**: Why?

610 **R1**: There are thousands of designs. Just tweak, they will become millions. By tweaking a design, you can beat these markers if you want.

611 **R2**: Why?

612 **R1**: You cannot fight complexity with such simplification.

613 **R2**: But you are fighting.

614 **R1**: Yes.

615 **R2**: Why?

616 **R1**: The aim is to provide a simplified framework.

617 **R2**: What is its use when you say it will not work in all cases?

618 **R1**: It is a guideline.

619 **R2**: Why so?

620 **R1**: Because it provides neither the exact dimensions of the microfeature, overhang, and shape, nor their exact relative dimensions.

621 **R2**: Why?

622 **R1**: To fit in various types of AM.

623 **R2**: Do you mean not to fit in any type of AM?

624 **R1**: It requires your understanding.

625 **R2**: But you have just said it would act like the police. Do you mean they will act without having the power to enforce?

626 **R1**: Yes. This is what a framework is [101-102].

Dialogue 9

Boundary 2

627 **R2**: In Boundary 2, you say pre-processing, interlayer-processing, and post-processing are not meant to change size and shape. Can you clarify why you use both ‘size’ and ‘shape’? Why not just one of the two?

628 **R1**: Which one do you suggest?

629 **R2**: Shape, because we are talking about a shaping technique, not a sizing technique.

630 **R1**: When we change size without changing the geometrical shape, the resulting entity is still considered a new shape. Therefore, to inform that ‘shape’ means only a geometrical shape, both are used.

631 **R2**: When we change size, shape always changes. Then why not use only the size?

632 **R1**: Because it does not provide the complete information—it requires further explanation.

633 **R2**: Can you show how pre-processing changes size and shape?

634 **R1**: Suppose we make a structure on a substrate using DED. When the structure is separated from the substrate, this structure is an AM part. When the structure is not separated from the substrate, the part is the combination

of the structure and the substrate. This combination is not an AM part. The shape and size of the combination is changed due to the shape and size of the substrate. The substrate is not made during the processing stage. It is fabricated before the processing stage and is then fitted into a DED machine. The stage during which it is fabricated is a pre-processing stage. The final part, i.e., the combination of the structure and the substrate, thus formed has been changed due to pre-processing.

635 **R2**: Can you give an example of how pre-processing does not change size and shape?

636 **R1**: When a part is separated from a substrate, the shape and size of the part is not changed by pre-processing.

637 **R2**: But a substrate is an essential component of AM fabrication [103-104]. How do you associate it with pre-processing?

638 **R1**: A substrate can be customized to various shapes, which will facilitate making various parts. Customization of the substrate does not happen during the processing stage. The customization occurs during pre-processing stage. Repair and refurbishment [105] by DED is one of the examples where pre-processed part is processed by AM.

639 **R2**: But repair happens on a broken part. How can you say it is a pre-processed part?

640 **R1**: It is a pre-processed part because the final part is not made from scratch but relies on previous processing to furnish it. The final part is repair plus broken part. The repair is akin to an AM part. We would not call the broken part a pre-processed part if we separate the repair from the broken part and present the repair as a new part. This will let the broken part act like a substrate.

641 **R2**: But I have heard pre-processing is used to customize materials, i.e., to make specific powder [106], pellet, wire, filament, resin, or to change numerical files, etc [107-108].

642 **R1**: These customization do not change size and shape.

643 **R2**: In the framework, there is only one outer boundary as given by Boundary 2. Is it sufficient?

644 **R1**: Yes. A technique is supposed to have only one outer boundary. This is a universal fact.

645 **R2**: If this is a universal fact, what is the need for a framework? Does one need a framework to know the universal fact?

646 **R1**: We need it, because we shift the boundary as per our convenience.

647 **R2**: But Boundary 2 does not talk about a process, it talks about post-processing and other processing.

648 **R1**: Post-processing is one of the reasons we shift it. Therefore, to fix it, its scope needs to be fixed.

649 **R2**: But you forget why the notion of post-processing exists. The arrival of post-process signals the departure of process. It means, the start of a post-process is the end of a process. The moment post-processing starts, the boundary of the process ends. The boundary lies between its process and post-process. Thus, there exists a natural boundary. What is the need for a boundary to be defined by the framework?

650 **R1**: We do not work process-wise. We work machine-wise. When we work in an AM machine, we assume we work in an AM process. When we finish working in the AM machine and start working in another machine, we assume we have finished working in an AM process and start working in another process. We do not want to believe that a machine cannot always be synonymous with a process.

651 **R2**: Can you give an example?

652 **R1**: We make a part using DED. When we are working in a DED machine, we are working in an AM process. When we finish making the part, we leave the DED machine, i.e., we have finished working in an AM process. Now, we want a machine it remove its surface roughness. We start working in a CNC machine, it means we are working in another process, i.e. a post-process. During the removal of surface roughness, we change the size and shape of the part. It is still a post-process for us, because we are working in a post-process machine. But we are not respecting the natural boundary of a process when we change the shape of the part. We are trespassing the boundary of the process. But we are not aware of it because we are not trespassing the boundary of the machine. For us, the natural boundary lies between two machines, i.e., the boundary between two machines is the boundary between two processes.

653 **R2**: You have given an extreme example. Can I give another one?

654 **R1**: Yes, sure.

655 **R2**: After making a DED part, I went to paint it. Painting is one of many post-processing [109] It does not change the size and shape of a part. The boundary between an AM machine and a painting machine is exactly the same as the boundary between the AM process and the painting process. Is it ok?

656 **R1**: Yes.

657 **R2**: When the boundary of AM process ends, then the boundary of post-process begins. Is it ok?

658 **R1**: Yes.

659 **R2**: But this is not what the framework says. It says a certain type of post-process exists within the boundary of AM, while some post-processes exist outside it.

660 **R1**: AM is divided into three stages: pre-process, process, and post-process [110]. There are boundaries between these stages. Shaping only happens when the pre-process stage ends and the post-process stage has yet to begin. It is the shaping that determines the boundary: at the beginning, it determines between pre-process and process stage; at the end, it determines between process and post-process stage. What the framework says – post-processing is not supposed to change size and shape – is not a new discovery but has been part of AM since its beginning.

Please note that it is not an AM process that is divided into three stages, but it is the fabrication using an AM process is divided. Therefore, post-processing is part of AM as long as it is one of the three stages of AM. It will be one of the three stages of AM as long as it does not change the shape of an AM part; because when it changes the shape, it is no longer part of AM that has exclusively chosen an AM process during its process stage to do shaping.

661 **R2**: Can you clarify the example I gave?

662 **R1**: When painting is used to paint a DED part, the painting process is part of AM as the third stage of AM. It is within the boundary of AM. This is the boundary that is mentioned in the framework. But the boundary you mention that exists between an AM process and painting is the boundary between the second and the third stage of AM. The confusion started because you mistook the boundary between an AM process and painting with the boundary between AM and painting.

663 **R2**: Are you saying AM is different from an AM process?

664 **R1**: Yes, but confusion arises because we use them interchangeably.

665 **R2**: How are they different?

666 **R1**: AM is a method or tool to provide a part, using an AM process as its main tool. Therefore, AM is divided into three stages, in which the second or main stage is meant for an AM process.

667 **R2**: Are you saying an AM process is not a method or tool to fabricate a part?

668 **R1**: An AM process is a set of steps. Since a method can also be a set of steps, the AM process is a method as well. The set of steps is meant to make a part, while a tool is also meant to make a part. Therefore, an AM process can also be a tool.

669 **R2**: So there is no difference between AM and an AM process.

670 **R1**: Have some patience.

671 **R2**: You are not answering.

672 **R1**: An AM process is a set of steps to make a part. What if the steps are used and you do not like the part? You iterate the steps and refine them. But you have limitations. These steps revolve around the layer-by-layer method. You do not have luxury to extend the range of steps. You rely on some more steps before and after the process steps to make a right part. The steps before are pre-process steps, and the steps after are post-process steps. AM is a set of steps when all steps are included, an AM process is a set of steps when pre- and post-process steps are excluded. When pre- and post-process steps are not required, AM is an AM process.

673 **R2**: Are you saying painting process is part of AM because painting is used as a post-process?

674 **R1**: Yes. The painting process is part of AM to finalize a part, but it is not a type of AM.

675 **R2**: Can you clarify the example you gave about CNC machining of a DED part?

676 **R1**: When post-process CNC machining changes the shape of a DED part, this post-processing is not the third stage of AM. To be the third stage, it must not change the shape. Therefore in this case, AM has no third stage. This makes the second stage of AM, i.e., the DED process the boundary of AM. Thus, the boundary of AM and the AM process coincides. Post-processing, i.e., CNC machining is outside the boundary.

677 **R2**: What is its consequence?

678 **R1**: The part is not finalized within the boundary. Therefore, it is not an AM part. The final process is not AM.

679 **R2**: It is a negative statement. Can it not be positive?

680 **R1**: You can say it differently. The part is finalized outside the boundary. Therefore, it is a HAM part. The final process is HAM.

681 **R2**: If it is not an AM part, is it a HAM part?

682 **R1**: Yes.

683 **R2**: Are you saying a machined or welded part is a HAM part because it is not an AM part?

684 **R1**: I am saying only in the context of AM.

685 **R2**: Suppose a part is made by CNC machining. DED is used as a post-process to add some features on top of the part. The final part has 80% contribution from machining and 20% from AM. Since AM is used as post-processing, can you clarify where the boundary is?

686 **R1**: AM is considered a main process, while machining is a pre-process---

687 **R2**: It is wrong. Machining is a main process, while AM is a post-process.

688 **R1**: I am saying AM a main process not because it has more contribution than machining, but because it is the main process from the perspective of AM.

689 **R2**: Why do you use the perspective of AM when AM is not a main process?

690 **R1**: Can I explain what perspective means?

691 **R2**: Please.

692 **R1**: Perspective means how one observes a system. Observation does not change the fact, it only presents it differently. For example, saying A is bigger than B instead of saying B is smaller than A does not change the fact, i.e., the relation between A and B. When I say I am using perspective of AM, I am not changing the relation between machining and AM. I am not changing the contribution of machining. I am only checking the contribution of machining after checking the contribution of AM. Since I am checking AM first, AM is at the central stage or main stage of my observation. Therefore, I say AM a main process and machining a pre-process.

693 **R2**: But where is the boundary?

694 **R1**: Between pre-process and main process.

695 **R2**: So machining is outside the boundary.

696 **R1**: Yes.

697 **R2**: So the final process is HAM.

698 **R1**: Yes.

699 **R2**: So pre-process is outside the boundary of AM.

700 **R1**: Yes

701 **R2**: Why do you call it a pre-process stage when it is not one of three stages of AM?

702 **R1**: Because this stage comes before the main stage.

703 **R2**: How can it be one of the three stages when it is outside the boundary?

704 **R1**: The first and the second stage, i.e., pre-process and post-process stage are not meant to change shape. When they change, they are not part of AM. They are no longer stages of AM. Then AM has only one stage, i.e. the second or the process stage. Other stages are mentioned only to show their positions in a sequence.

705 **R2**: You change the meaning of ‘pre-process’ based on a change in the situation. Is it right?

706 **R1**: This is what it is.

707 **R2**: Should we say if pre- or post-process stage is outside the boundary, it is HAM?

708 **R1**: Yes.

709 **R2**: Suppose we do interlayer machining during DED. Can you suggest where the boundary is?

710 **R1**: We do interlayer machining after we print some layers using DED. Let us consider we print fifty layers and do interlayer machining to decrease the size. The machining is used as post-processing of an AM structure of fifty layers. Therefore the boundary lies between an AM process and post-process.

711 **R2**: But I can say the same thing differently. When we machined a fifty-layer AM structure, we got a shaped structure to deposit further material on it using DED. This shaped structure can be considered a pre-processed part. We again print on this pre-processed part. Therefore, the boundary lies between pre-process and an AM process.

712 **R1**: Yes. The same boundary passes between pre-process and process, and between process and post-process.

713 **R2**: Suppose I change the perspective, can hybrid AM be called hybrid CM?

714 **R1**: How?

715 **R2**: Can I give an example how post-processing can be observed from a different perspective?

716 **R1**: Yes.

717 **R2**: Consider post-process machining. If the combination of AM and machining is hybrid AM because machining is used to overcome the problems of AM, it can also be argued that the combination is hybrid CM because machining is applied to extend its own capability. How is it extending? If machining is used along with a fraction of AM, it can do wonderful – this is how machining is extending its capability. This is how it can be claimed that machining is extending its capability. Therefore, why should I call it hybrid AM? I must call it hybrid CM. Therefore, what Boundary 2 mentions as hybrid AM can also be mentioned as hybrid CM.

718 **R1**: The framework is not about name but about concept. It emphasizes that the example you are giving is not of AM. Therefore, you must not call it AM.

719 **R2**: If the framework is not about name, what does it matter if I call it hybrid CM?

720 **R1**: You can. It will indicate the same thing, i.e., the process is not purely additive.

721 **R2**: The framework says post-processing is not meant to change size and shape. Does it mean the framework is based on a premise that post-processing is widely used in AM?

722 **R1**: Yes. Post-processing is widely used [111].

723 **R2**: Does it mean AM is not a net-shaped technology?

724 **R1**: If the aim is to make non-critical parts, prototypes [112], hobbyist parts, visual models, conceptual models, AM is a net-shaped technology. Otherwise, it is a near-net-shaped technology [113-114].

725 **R2**: Is it not misleading to call AM a rapid technology if post-processing is almost always used?

726 **R1**: Post-processing does not decrease its rapidity enough to make it slower than other technologies [115]

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