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(RESEARCH ARTICLE)

Future manufacturing integrating additive and subtractive processes: A theoretical framework

Md Ferdus Al Hossain [1] and Md Shakil Molla [2,*]

[1] *Matrighor Limited, Hemayetpur, Tetuljhora Road, Savar, Dhaka-1340, Bangladesh.*
[2] *Department of Electrical and Electronic Engineering, Bangladesh Army University of Engineering and Technology, Qadirabad, Dayarampur, Natore-6431, Bangladesh.*

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Abstract

Models that are more flexible, adaptable, and good for the environment are increasingly becoming the norm in manufacturing systems of the future. Additive manufacturing (AM) offers freedom, while subtractive manufacturing (SM) provides accuracy and surface quality. This blend of technologies helps producers construct intricate forms while utilizing less material and making their products operate better. There aren't any theoretical frameworks that all hybrid AM-SM systems follow when they are designed, built, and optimized, even though they are useful in real life. This paper gives us a whole theoretical framework for modeling trade-offs at the system level, making decisions, and bringing processes together. The framework tries to give researchers and real-world users a place to start by borrowing ideas from process planning, multi-objective optimization, and cyber-physical systems. The article also discusses future research goals and policy consequences to make it easier for people to use hybrid manufacturing systems.

Keywords: Hybrid Framework; Smart Manufacturing; Cyber-Physical Systems; Additive Manufacturing; Optimization

1. Introduction

Manufacturing systems are going through a big change because of fast changes in technology, more competition around the world, and more demand from customers for eco-friendly and personalized products [1]. People have long respected traditional subtractive manufacturing (SM) procedures like milling, turning, and drilling because they are accurate, give surfaces a great polish, and have been demonstrated to be reliable in this changing environment [2]. But these processes can't make lightweight lattice structures or complicated interior shapes very well, and they often waste a lot of material [3].

Additive manufacturing (AM), commonly known as 3D printing, has changed the way we design by allowing us to make complicated forms and lightweight parts that are optimized without the need for expensive equipment [4], [5], [6]. AM lets you utilize less material, create freely, and put together multiple parts into one solid structure [7], [8]. However, AM has its own problems, such as a rougher surface polish, less accurate dimensions, anisotropic mechanical properties, and production rates that are often slower than those of traditional methods[9], [10].

One option to get the most out of both AM and SM is to combine them into a single hybrid production system. This way, you can have the best of both worlds while minimizing the downsides of each method [11]. By employing AM to build near-net-shape parts with intricate shapes and then SM to improve important surfaces and features, manufacturers may be able to achieve a greater degree of quality and usefulness than they could with either process alone [12], [13]. This

* Corresponding author: Md Shakil Molla.

combination could lead to new ideas in fields where performance and weight optimization are very important, such aerospace, medicine, cars, and energy [14], [15], [16].

The growth of hybrid additive-subtractive systems is also very much in line with the main ideas of Industry 4.0, which stress smart, connected, and adaptable manufacturing environments [17], [18], [19]. Cyber-physical integration can make hybrid systems better by making it easier to make decisions based on data, control processes that change over time, and keep an eye on things in real time. These changes make parts work better and use more resources, are more sustainable, and make manufacture more efficient [20], [21], [22].

Even with these chances, it will be hard for hybrid AM-SM systems to be developed and widely used [23]. There aren't any complete theoretical frameworks right now to help with the design, planning, and optimization of integrated manufacturing systems [24]. Instead of rigorously modeling how processes interact, what trade-offs they make, and how they make decisions, most research focus on case-specific experimental demonstrations. When combining two processes that are basically different, you also need to think about process sequencing, machine dynamics, material behaviors, and quality assurance methods very carefully [25].

This study tries to fill in the gaps by proposing a theoretical framework for future manufacturing that integrates both additive and subtractive techniques. The framework looks at process integration strategies, lists significant decision factors and constraints, and sets up multi-objective optimization approaches to find a balance between opposing goals including cost, quality, time, and environmental impact. This framework's goal is to help both industry and academic research make the most of hybrid manufacturing systems by giving them a well-organized base.

The demand for parts that are light, can perform a lot of things, and can be tailored to each customer's needs is what is pushing the use of advanced manufacturing methods. The aerospace, medicinal, automotive, and energy industries are asking for more and more parts with complicated interior shapes and smooth surfaces. These parts can't be made efficiently with just AM or SM.

Hybrid AM-SM systems can:

- Make shapes more complex while keeping accuracy.
- Reduce lead times by combining processes in a single setup.
- Improve sustainability through material savings and reduced energy consumption[24].

This paper aims to:

- Develop a theoretical framework for integrated AM-SM systems.
- Identify decision variables and constraints relevant to hybrid process planning.
- Formulate multi-objective optimization models addressing trade-offs between cost, quality, time, and sustainability.
- Provide guidelines for future research and policy development.

It is a big step forward in manufacturing technology to combine additive manufacturing (AM) and subtractive manufacturing (SM) into hybrid systems. This could lead to the production of high-performance, complicated parts with better functional capabilities. To integrate effectively, though, you need to have a clear understanding of process topologies, decision variables, and built-in limits.

2. Hybrid AM-SM Process Integration

Using both additive manufacturing (AM) and subtractive manufacturing (SM) in hybrid systems is a big step forward in how things are made. We might be able to make parts that are better, do more things, and work better. But to do it right, We need to know a lot about process architectures, how decisions are made, and what the limits are that come with it that is shown in Figure 01.

2.1. Process Architecture

There are two main ways to put together hybrid AM-SM systems: sequential integration and concurrent integration.

- Sequential Integration: This plan calls for doing AM and SM work in distinct steps, generally on different machines. The first step is to employ AM methods to make parts that are close to the right shape. After that, SM machines finish the parts. You can make each process better on its own with sequential integration. It also gives you more methods to employ the machine tools you already have. But it makes it harder to work with parts, move them around the appropriate way, and build fixtures. You might need to undertake other things, like heat treatments and inspections, in between to solve any size problems and strains that are still there.

- Concurrent Integration: This is when you put together features from both AM and SM into one machine tool. With this configuration, you can switch between additive deposition and subtractive finishing without having to remove the item off the printer. This makes it less likely that you'll mess up when you move the part and makes the shape more accurate overall. Concurrent systems may add and remove materials on the fly, which provides designers more freedom and makes processes more flexible.It still requires a lot of time and money to build and keep hybrid devices up to date.

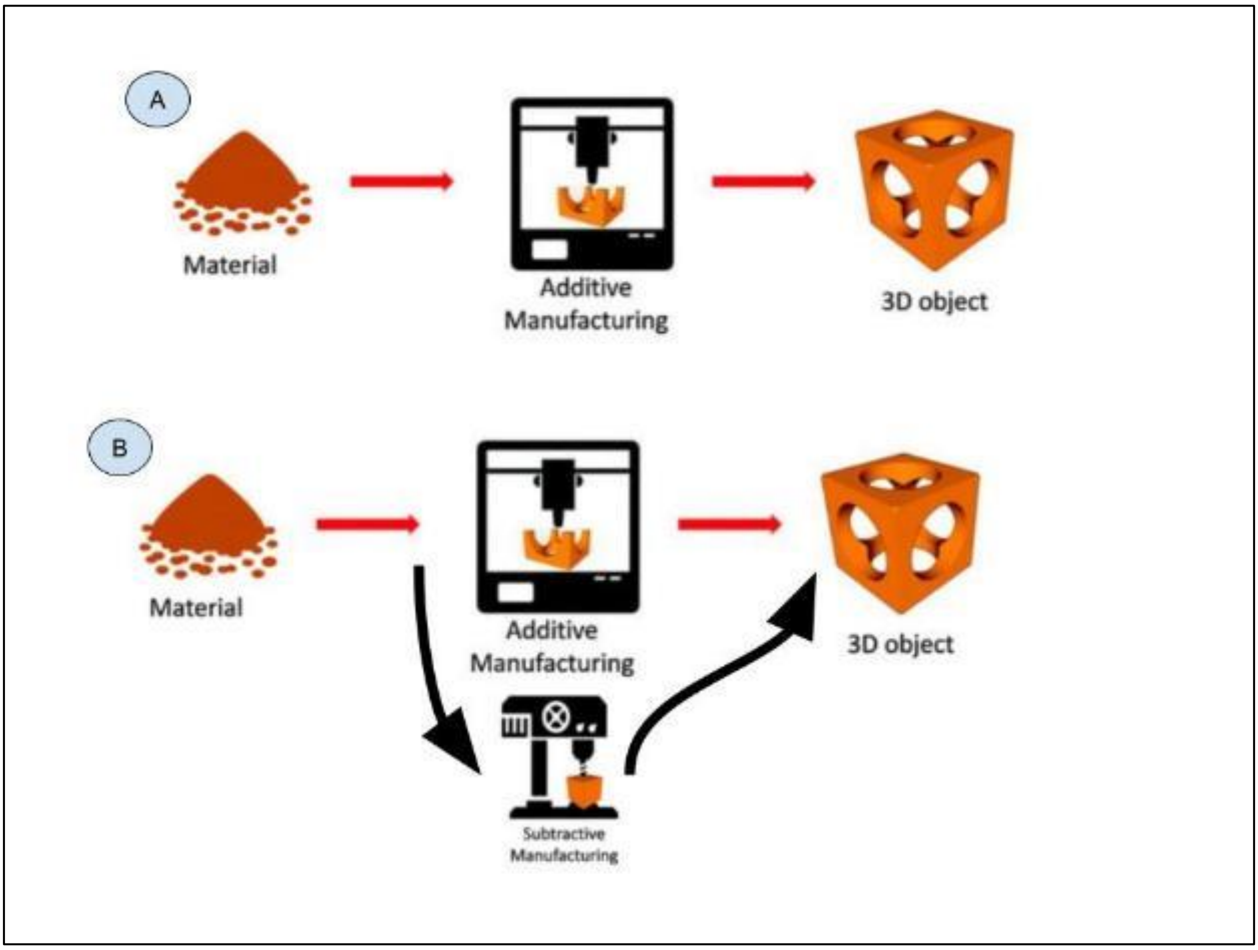

Figure 1 Hybrid AM-SM Process Integration

Before we choose between sequential and concurrent systems, we should think about how hard the parts are, how many we need to make, and how much money we have to spend. Concurrent systems are the best for accuracy and working together. But for small production runs or when using equipment that is already in place, sequential arrangements could work better.

2.2. Decision Variables

We need to think carefully about the major decision variables that affect part quality, production efficiency, and the system's overall performance too make sure that AM and SM processes operate well together in hybrid systems.

- **Build Orientation and Support Structures in AM**: The way a product is orientated during additive manufacturing affects how smooth its surface is, how strong it is, and whether or not it needs support structures. Optimizing orientation means we require less support material, we have to do less post-processing, and the build is more reliable.

- **Tool Paths and Cutting Parameters in SM**: During the subtractive stage, we need to determine the optimal ways to cut, feed, and depth of cut to produce the right surface finishes and tolerances while also cutting down on machining time and tool wear. It's also very crucial to pick the correct equipment and cooling methods to keep the pieces' surfaces and dimensions the same.
- **Process Sequence and Transition Points**: When to convert from AM to SM operations (or the other way around in re-entrant hybrid processes) is very crucial. It's vital to pick transition points that find a balance between finishing accuracy and the speed at which materials are deposited. When making a decision, think about how stiff the middle section is and how easy it is for cutting instruments to get to it.

These aspects that go into making a decision are very dependent on each other, thus they all need to be improved at the same time to develop a strong hybrid process plan. Advanced simulation tools and methods for maximizing several goals can aid with this difficult decision-making process.

2.3. Constraints

We need to consider the different problems that hybrid AM-SM systems have to cope with when we are planning a process or developing a system.

- **Geometric Limitations Due to Tool Accessibility**: The tools' shapes and the way the machines move make it hard to reach and make certain features. During the AM stage, tools may have trouble getting to complex internal structures in later SM stages. This means that we need to plan and create carefully.
- **Thermal Stresses and Residual Distortions**: The AM process often makes areas with strong heat gradients, which can lead to residual strains and potential deformities. These thermal effects can make later machining less accurate, therefore they need to be fixed with things like interim heat treatments or in-situ stress release.
- **Machine Workspace and Fixture Compatibility**: At all stages of the process, hybrid systems must be able to fit the full part in the machine workspace. It is highly crucial to design fixtures such that pieces stay stable and in line, especially while transitioning between adding and removing parts. The size of the machine, how well the fixture fits, and the forces that hold the fixture in place can all make it hard to manufacture parts that are bigger or more sophisticated than they should be.

To solve these difficulties, we need to look at the big picture and consider things like designing for hybrid manufacturability, simulating processes, and watching and controlling things in real time. By carefully considering architectural possibilities, decision criteria, and limits, hybrid AM-SM systems can attain their full potential in creating high-performance parts for the next generation.

3. Theoretical Framework

An integrated theoretical framework needs to be established in order to systematically build, control, and improve hybrid additive-subtractive manufacturing (AM-SM) systems. This framework needs to take into account the intricate connections between digital controls, physical processes, and different performance targets so that manufacturers can get the most out of hybrid methods.

3.1. Cyber-Physical Integration

We could call hybrid additive-subtractive manufacturing (AM-SM) systems cyber-physical systems (CPS). These systems use both physical manufacturing methods and computer intelligence, strong control systems, and the ability to observe things happening in real time. The CPS paradigm connects the digital and physical world. This makes next-generation manufacturing systems more intelligent, responsive, and adaptable than is shown in Figure 02.

CPS runs a hybrid manufacturing system with a network of built-in sensors that always gather information from both the additive and subtractive processes. These sensors keep a watch on a number of important process variables, such as variations in temperature, residual stress, the movement of the melt pool, the roughness of the surface, changes in size, the wear rates of the tools, and the machine's vibrations. The data streams that are gathered are transferred to computers that are either centralized or spread out for analysis and decision-making[26].

We can use adaptive feedback loops with data analytics that happen in real time. These loops let the system change process settings on its own while it is being created. This includes things like the power of the laser, the speed of the scanning, the thickness of the layers in AM, and the cutting speed or feed rates in SM. These closed-loop innovations assist reduce faults, improve dimensional accuracy, and make sure that the quality of the parts stays the same throughout the hybrid manufacturing cycle.

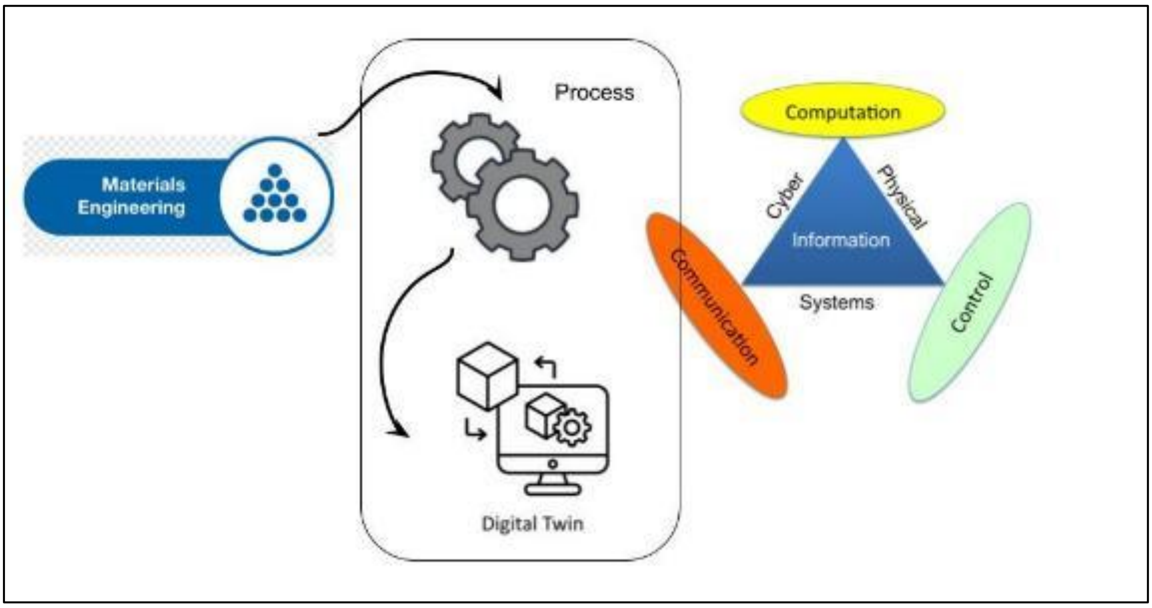

Figure 2 CPS Based Future Manufacturing

CPS integration also makes it easier to undertake predictive maintenance. This type of maintenance always examines seeing how well important tools and machine parts are working. By looking at patterns of problems and wear and tears, the system can forecast when things could break down and plan maintenance chores ahead of time. This helps the equipment last longer and saves down on downtime that isn't needed.

One of the best things about CPS is that it enables us to make digital twins. These are digital copies of the genuine hybrid manufacturing system that always have the most recent data from the real world. Before true production starts, digital twins are a wonderful method to try out changes to processes, see how a system will perform in different conditions, and make process workflows more efficient. They also help with virtual commissioning and what-if studies, which speed up the process of getting a product to market and lower the risk of needing to change it.

Smart hybrid production systems that follow the rules of Industry 4.0 are made possible by cyber-physical integration. CPS helps manufacturers become more flexible, more productive, and develop better products in places that are getting more complicated and changing all the time. It does this by allowing systems to make themselves better, change in real time, and be powerful all the time.

3.2. Multi-Objective Optimization

It is inevitable for hybrid additive-subtractive manufacturing (AM-SM) systems to have to make hard choices between goals that are often at odds with each other. Manufacturers need to keep in mind all these aspects at once: the cost of making the product, the time it takes to process it, how it affects the environment, the quality of the parts, and how well it works. All of these things are necessary to get results that last, work well, and are competitive in the market.

The proposed theoretical framework combines Multi-Objective Optimization (MOO) methods to handle these trade-offs in a methodical approach. MOO helps individuals make choices by guiding them through the difficult solution space and helping them find process configurations that best balance conflicting priorities.

The optimization problem can be written as:

$$min\ \{C, T, E\},\quad max\ \{Q, F\}$$

Where:

- C: The entire cost of making something, which includes the cost of materials, energy, labor, using machines, and keeping them in good shape. This score tells wehow competitive and economically sound something is.
- T: The total time it takes to process, which includes the time it takes to put up, take down, set up, and change procedures. It's crucial to keep T as low as possible so that wecan get more work done and cut down on lead times.
- E: the impact on the environment, which may be measured by factors like total energy use, material waste, greenhouse gas emissions, and how well resources are used overall. This aim fits with both the norms that must be obeyed and the goals for global sustainability.
- Q: The quality of a part is determined by how smooth the surface is, how exact the dimensions are, how well the geometry matches, and how many faults exist inside. A lot Q makes sure that everything works properly and that customers are happy.
- F stands for functional performance, which is how well the item can meet the mechanical, thermal, and operational needs of its specific usage. This includes factors like how well it conducts heat, how strong it is against fatigue, and how well it can hold a load. Because improving one objective often necessitates sacrificing another (e.g., achieving higher quality might increase cost and time), Pareto front solutions offer the finest trade-offs because improving one aim usually implies giving up another. For example, achieving greater quality can require spending more time and money. A Pareto front is made up of solutions that are not dominated. This indicates that we can't make one objective better without making at least one other objective worse.

By looking at the Pareto front, decision-makers can choose a final process configuration that fits with their strategic goals. For example, they can keep production costs and part quality within acceptable bounds while limiting the impact on the environment. We may use this to create wise trade-offs instead of just going with your gut or what you've learned in the past. To efficiently explore the difficult, high-dimensional solution space, advanced computer techniques are used. Genetic algorithms, particle swarm optimization, and multi-objective evolutionary algorithms are some of the greatest tools for solving hybrid manufacturing problems because they can deal with nonlinearities, discrete variables, and many goals that conflict with each other. Also, dynamic optimization is possible when real-time data from cyber-physical systems is combined. This means that solutions are always growing better based on changing process circumstances and sensor feedback. This feature lets us schedule things flexibly and makes modifications on the fly to preserve performance at its optimal, even when operational limits change.

By utilizing a stringent multi-objective optimization technique, manufacturers can get the most out of hybrid AM-SM systems in the end. This lets them do better in all three areas: the economy, the environment, and technology.

3.3. Decision-Making Strategies

We need to combine the cyber-physical data layer with optimization insights in order to make smart decisions in hybrid AM-SM systems. This will help us make decisions in real time and for the long term. The suggested theoretical framework is based on the following strategies:

- **Adaptive Scheduling Based on Real-Time Sensor Data**: Dynamic scheduling enables the system adjust the order of processes, move resources around, and change the timetable of activities when it identifies problems or priorities change. For example, if an issue is identified during the AM stage, the system can wait to do the next SM operations until the problem is rectified.
- **Dynamic Adjustment of AM and SM Process Parameters**: Using real-time data, process parameters like laser power, scanning speed, layer thickness in AM, and cutting speed or feed rates in SM may always be made better. This minimizes the chance of mistakes, improves the surface, and makes the measurements more precise.
- **Predictive Analytics for Defect Anticipation and Transition Optimization**: Machine learning models can look at historical and present data to forecast what problems with quality or defects might develop before they do.

Together, these strategies create a closed-loop control environment that enhances system responsiveness and adaptability, ultimately supporting higher levels of automation, consistency, and overall system intelligence.

4. Future Research Directions

4.1. Real-Time Closed-Loop Control Systems

In the future, researchers should exclusively work on establishing closed-loop control systems that work in real time and are solely for hybrid AM-SM processes. These systems use smart control algorithms and high-quality sensor data, so wecan always watch operations and alter their settings on the fly. These kinds of talents would make things more exact, cut down on mistakes, and make sure that parts are always of the same high quality, even when things change or procedures are put on hold. Adaptive optimization and predictive mistake correction with machine learning models can help the system function better and faster.

4.2. Advanced Multi-Physics Simulation Tools

It's hard to understand how thermal, mechanical, and material events affect each other throughout both the additive and subtractive stages of hybrid manufacturing. Researchers and practitioners will be able to generate better predictions and get better outcomes from their work if they construct advanced simulation tools that include multi-physics models, like changes in temperature, changes in residual stress, and changes in microstructure. We can use these technologies to come up with designs that can be manufactured in more than one manner, test procedures in a virtual world, and save time and money by not having to try things out.

4.3. Lifecycle Assessment and Sustainability Metrics

Researchers should employ full lifecycle assessments (LCA) in the future to find out how hybrid AM-SM processes affect the economy and the environment. To make sure that hybrid manufacturing processes meet global sustainability requirements, it is vitally important to know how much energy they use, how much carbon they leave behind, how well they use resources, and what happens to them when they die. Using LCA data in decision-making frameworks can assist improve processes so they have less of an impact on the environment while yet keeping the economy healthy.

4.4. Human-Robot Collaborative Frameworks

Advancing **human-robot collaboration (HRC)** in hybrid manufacturing cells offers significant potential to enhance flexibility, safety, and productivity. We need to learn more about how to build smart robots that can aid people with things like moving things, setting up fixtures, verifying things, and finishing work that changes. HRC frameworks should be simple to use, let people and robots work together safely, and enable people design projects as they come up. This will make it easier for machines and people to work together.

4.5. Integration with Industry 4.0 Technologies

Weshould also think about how to make hybrid AM-SM systems operate better by using AI-powered decision aids, cloud-based data analytics, and sensor networks that can connect to the Internet of Things (IoT). These technologies let wesee the whole production process from a distance and use data to make it better. More advanced digital twin models powered by AI can demonstrate how a system will work and what will happen. This makes it easy to do maintenance ahead of time, keep things up to date, and get things done faster.

5. Conclusion

The next generation of advanced manufacturing will be far better off with hybrid systems that combine AM with SM. Many sectors need parts that are lightweight, high-performance, and highly adaptable. Hybrid manufacturing techniques are an excellent way to meet these needs. They combine the geometric freedom and material efficiency of AM with the accuracy and higher surface quality of SM.

This study offers a whole set of ideas to help make, improve, and use hybrid AM-SM systems. The method integrates concepts from CPS, multi-objective optimization, and adaptive decision-making to handle the inherent complexity of hybrid processes. Using real-time sensor data, predictive analytics, and smart feedback loops, manufacturers can constantly change their processes, improve the quality of their products, and make their operations more efficient.

Finding a balance between goals like cost, time, quality, environmental impact, and functional performance is highly crucial with multi-objective optimization. People may make informed choices that are good for both the company and the environment by using Pareto front analysis and sophisticated evolutionary algorithms.

This research also talks about crucial limits and choices that come with hybrid process planning. It underlines how important it is to have a whole plan that takes into consideration the limits of geometry, the effects of heat, and the limits of machine resources. By adding CPS and digital twin technologies, the framework becomes even more flexible and strong. This supports the idea of fully autonomous and self-optimizing production environments that are part of Industry 4.0.

More research is needed in the future to make real-time closed-loop control systems, multi-physics modeling tools, and lifecycle sustainability assessments better. We will be more flexible and resilient if we accept that robots and people may work together and combine hybrid systems with bigger Industry 4.0 ecosystems.

In conclusion, this study's theoretical framework sets the stage for getting the most out of hybrid AM-SM manufacturing. It looks at both technical and strategic elements to lay the foundation for developing smart, long-lasting, and very flexible manufacturing systems. As companies keep pushing the limits of new products and better operations, hybrid manufacturing will play a big role in shaping the future of manufacturing around the world. This will be achievable thanks to strict theoretical models and making decisions based on evidence.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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