POLITECNICO DI TORINO
Engineering and Management

Master Degree Thesis

Literature review of short-term production planning for Additive Manufacturing (3D printing).

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Abstract

This thesis presents a literature review to explore the challenges of scheduling in Additive manufacturing (AM) focusing on innovative scheduling methodologies to tackle the unique challenges of AM processes. Scheduling in (AM) faces challenges such as material and process selection, part geometries, integration with existing systems, customization demands, material availability, which traditional scheduling methods often fail to resolve.

Through literature review, optimization strategies and domain expertise papers, thesis shows novel scheduling strategies designed to enhance key performance metrics like lead time, throughput, and energy consumption. The thesis reviewed numerous papers on short term production planning of AM, the state-of-the-art methodologies found in the literature review include principles from optimization and operations, integrating automation, robotics, and AI to streamline AM production planning.

Conclusive literature review remarks suggest that these adaptive scheduling strategies requires advanced scheduling algorithms, real time monitoring, and seamless integration of automation and robotics to ensure efficient, high-quality production, improve productivity, reduce costs, and accelerate time to market for AM produced components. By advancing efficient scheduling methodologies, the thesis aims to support Additive Manufacturing (AM)s broader integration into mainstream manufacturing.

Contents

Chapter 1

Introduction

Additive manufacturing (AM), is a process of creating a three Dimension object, 3 D printing has revealed as a technology transformative in modern manufacturing processes. Unlike the old methods subtractive, Additive Manufacturing builds objects layer upon layer from digital 3D designs CAD, offering unparalleled customization, efficiency and flexibility [42].However, the adoption of Additive Manufacturing in industrial settings meets some challenges, particularly in optimizing production schedules to minimize costs and minimize utilization.

Scheduling of Additive Manufacturing processes shows unique complexities compared to conventional manufacturing. Traditional scheduling methods often fail to address the dynamic nature of Additive Manufacturing, where different factors like machine capabilities, material availability, and part geometries play Important roles [3]. As a result, there is a growing need for advanced scheduling strategies tailored specifically to AM environments.

This thesis is a literature review looks into how we can schedule tasks in 3D printing (or Additive Manufacturing) more efficiently. The review methods think about many things, like the type of materials used, which machines can do what, the order in which parts are made, and how they are positioned during printing.

It studies how good scheduling can improve important measures like how long it takes to make something, how much can be produced, and how much energy is used. If companies that use 3D printing can plan their schedules better, they can make things faster, cheaper, and more efficiently, helping them get their products to market quicker.

In short, the goal of this thesis is to present a literature review to explore the challenges of scheduling in Additive manufacturing (AM) focusing on innovative scheduling methodologies to tackle the unique challenges of AM processes.

This thesis examine various research papers, scheduling of Additive Manufacturing processes with the purposes of improving efficiency and utilisation resources. By conducting the principles from optimisation research,operations research, and Additive manufacturing domain knowledge,the scheduling algorithms novel can be developed to address the complicated details of additive manufacturing. Such algorithms must consider various constraints, including material properties machine compatibility,part prioritization and build orientation.

This Thesis explores the potential Challenges of scheduling on the most key performance metrics such as lead time,throughput, and energy consumption. By manufacturers,optimizing scheduling decisions,can increase productivity, reduce production costs, and accelerate time to market for Additive Manufacturing produced components.

1.1 Background of Additive Manufacturing

As the french scientist Alain Mehaute in 1984 patented Additive Manufacturing is a known technology in different feature like the addition of material with different methods (powder or wire) in the place of the subtraction of material from the law parts. The conceptual design phase and preliminary was introduced to reduce production cost and realization time for a prototype. Low scale mass production in past two decade also considered this method due to some advantages. This technic allows the construction of evolutionary shapes structure of complex design that are difficult to build through machining or traditional milling. For topological optimization usually create evolutionary shape these reasons important mass savings or increases in structure mechanical properties are obtained using Additive manufacturing [15].

In the early days the development of Additive Manufacturing (AM)'s was very short and the processes have reached high expectations and interest and also develop a unique exploitation dynamic industry and research, in this era different Additive manufacturing technologies principles and processes were invented and tested [41]. At this period more than 30 system providers are functioning in demanding market, the implementation and innovations shows the general focus on the role of Laser technology, shortcomings, its impacts and the future aspects points of interest,the present Issue proposes in Additive Manufacturing research with particular attention to the different employed technologies and the several possible applications.

The fundamental principle of underlying additive manufacturing is the layer-by-layer deposition of material to create a 3D object. This can be achieved through some various AM processes Stereolithography (SLA), SLS, (FDM),(EBM) [43].These technologies are the potential advantages given by 3d Design printing for the production of modern systems Biomedical engineering field,Civil,Mechanical and structures in Aerospace. Numerical, analytical and experimental knowledge and models are shown to exploit the potential advantages given by 3D printing for the production of modern systems and structures in aerospace, mechanical, civil and biomedical engineering fields. As modern technologies continues its journey toward maturity as a production technique the AM focus lies in achieving the mass production of customised products [13].

Currently the researchers and practitioners are increasingly focusing on developing advanced scheduling strategies tailored specifically to the intricacies of AM environments. These strategies leverage principles from optimization research, operations research, and domain-specific knowledge in AM to develop novel scheduling algorithms capable of addressing the intricate details of AM workflows.

1.2 Scheduling in Additive Manufacturing

Scheduling in additive manufacturing (AM) combines the systematic organization of production activities within AM processes, like 3D printing. This include allocating of materials, resources, involves machinery and labor, to specific tasks within specified time frames to ensure efficient operation, the high quality outputs, and timely order fulfillment. The characteristics of AM involves its potential to produce the complex geometries and customized parts directly from digital models, introduce specific challenges and opportunities for scheduling. The complexity of technology in AM also encompasses with different components of scheduling in 3D printing according [58].

- Job Sequencing: Calculating the order in which jobs are processed, considering factors like job priorities,due dates, and the specific requirements of each job. like (material, mechanical properties, color).
- Machine Allocation: Assigning jobs to specific Additive Manufacturing machines according on their capabilities, such as material, build volume, printing speed, and compatibility, to ensure the advantage use of the equipment.
- Batch Processing: connecting multiple parts into a single build job to maximize build space utilization and efficiency. This include strategic placement of parts to minimize support material use and post processing time.
- Maintenance Planning: Scheduling regular maintenance for AM equipment to maintain operational efficiency and prevent unexpected breakdowns, which can cause delays of production.
- Material Management: Ensuring materials are available and properly allocated to scheduled jobs, considering factors like material type, color, and specific properties required for the job.

- Post-Processing Scheduling: Allocating time for necessary post-processing steps, such as support removal,curing and surface finishing which are critical for achieving the desired quality and functionality of the printed parts.

As Scheduling in additive manufacturing involves its planning and organizing the production process to efficiently produce different parts. It's most component of Additive Manufacturing operations, especially as these technologies become more advanced into mainstream manufacturing. The main goal of scheduling is to optimize the use of resources, minimize production time, and ensure the time of delivery for high quality products.

1.3 Goals of the Thesis

Additive Manufacturing (AM), an innovative force in modern manufacturing, explain the introduction of unparalleled customization, efficiency, and flexibility by constructing 3 dimensional objects from digital CAD designs layer upon layer.This ability to produce the complex geometries that were previously unattainable marks a significant beginning from traditional subtractive manufacturing methods. anyway, integrating Additive Manufacturing into industrial operations faces valuable challenges, particularly in scheduling of production.

The only complexities of Additive Manufacturing like the complex interplay among machine capabilities, material availability, and part geometries require advanced scheduling strategies and technologies that advanced to the scope of traditional methods. These complexities necessitate the development of new methodologies adapted to the AM environment, aimed at optimizing production schedules to increase efficiency, resource utilization, and significantly impact key performance metrics like lead time, throughput, and energy consumption.

Introducing these challenges is vital for showing the full potential of Additive Manufacturing, especially like the technology transitions from prototyping to a feasible option for lowscale mass production, enabling the creation of complex and evolutionary shapes with significant advantages. The need for scheduling methods and efficient and adaptive is emphasized by the integration of Additive Manufacturing technologies like Fused Deposition Modeling FMD and Selective Laser Sintering (SLS) with the Computer Aided Design (CAD), which are major impact for the production of modern systems across most engineering fields. This literature review aims to explore the potential impacts of scheduling paradigms for Additive Manufacturing comprehensively and understanding scheduling Strategies that are specifically designed for Additive Manufacturing's unique key performance and metrics requirements.

1.4 Structure of the Thesis

This contextual of Thesis is divided into various sections as going to be seen by the rest of the document. The introduction is an important section in this Thesis, it generally gives a background information on scheduling in Additive manufacturing and a brief description of its history. The introduction also has sections of the goals of thesis,The goals of thesis describes the general issue that has necessitate thesis according to different articles, the thesis questions and the objectives that have been developed in this document have been used to provide a blueprint that will help in realizing the purpose of this thesis.

Additive Manufacturing section is the second chapter in this thesis, it serves to detailed information on AM, it contain additive manufacturing technologies which shows different technical strategies and methodologies on AM,additive manufacturing process and its advantages on industries is most welcome to introduce the impacts of scheduling and challenges according to the strategies have been used to identify the proper production scheduling in this modern industries of additive manufacturing.

Short Term Production Planning and scheduling of AM discuss on tailored strategy designed to optimize the efficiency and effectiveness of scheduling in AM. The fourth Chapter technological innovations and their impact on AM production Planning shows how Innovation Technologies improve scalable Production Process,leading customization and Challenges in real time scheduling,monitoring of AM. Conclusion Section combine the information provided in this thesis and summarize it to conclude scheduling strategies in AM, highlighting the importance of adapting to technological advancements and addressing the unique challenges in this field.

Chapter 2

Additive Manufacturing

The primary Principle of additive manufacturing is, it uses Computer Aided Design (CAD) generated 3D model directly to fabricate a three Dimension objects by adding successive layers of material and joining them. In new modern technology Additive manufacturing provide different advantage such as production efficient use of material, building materials and production flexibility [18]

In contrast traditional technologies, Additive Manufacturing in the beginning was limited to some Contexts. for example rapid prototyping, prototype and model making applications. AM technologies can be used to produce parts with extremely technology and it is the future according to traditional technology, what makes it different from traditional manufacturing is rather than starting with material and removing what you do not need instead you just add the parts that you need with different methods.

Basically building up a part with the material that are using AM which encompasses many different types of manufacturing processes, powder bed fusion where a large 3D printer spread powder into a building plate and essentially use a laser welder to weld a three dimensional sheet, shape it allows to take what a design engineer creates in CAD model and print it from scratch. AM enables the functional integration of multiple components into a single, more complex part, allowing for the production of the final product in one step. This process minimizes the need for assembly stages, shifting focus to post-production activities linked to the method of production itself. [33] additive manufacturing 3D printing have several production techniques defined in ISO/ASTM52900:2021 [30, 66] AM has a lot of unique characteristics and so as the manufacturing technology advances are adapting a lot of Medicine,Civil Engineering, aerospace product lines to include more additive and it is really integrate in the industry as a new method of manufacturing, additive really helps reduce the lead time in what it takes in traditional manufacturing. [21] Additive manufacturing is far less expensive at low and medium volume production, even though the unit production cost for a single additive component may be greater when compared to full-scale traditional production.

2.1 Additive Manufacturing Technologies

As per ISO/ASTM standards Additive Manufacturing (AM) technologies have revolutionised industrial practices by allowing for the creation of parts with highly complex geometries that traditional manufacturing methods cannot achieve [30].

Additive manufacturing technologies is divided into seven categories depending to techniques used to creates those products layer by layer, energy sources or fuse Material [32].

2.1.1 Vat Photopolymerisation

According to ISO/ASTM (2021), a vat refers to a substantial receptacle designated for holding liquid photopolymer. The technique utilized, termed photopolymerization, involves creating three-dimensional objects by strategically exposing radiation-curable resins, or photopolymers, to ultraviolet light in (**Fig 2.1**) . This exposure triggers a chemical reaction that solidifies the materials. This specific technology is limited to printing objects from polymer materials [70].

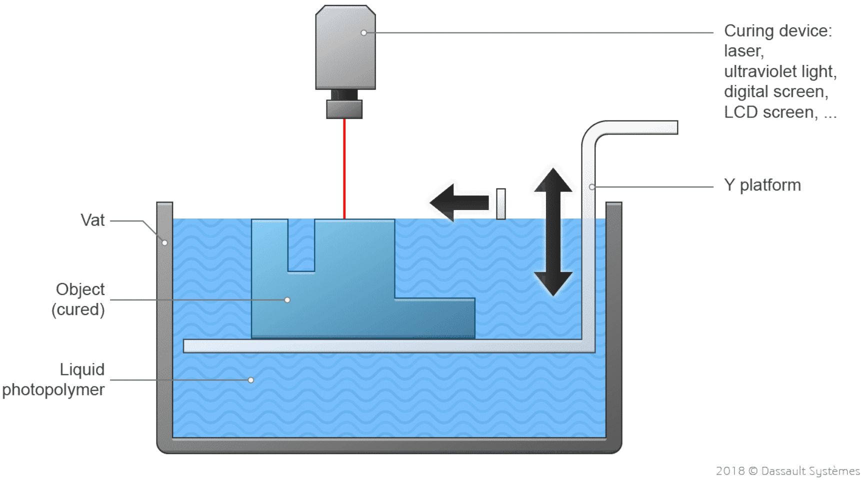

Figure 2.1. Vat process Photopolymerisation (source:VatProcess)

2.1.2 Powder Bed Fusion

Powder Bed Fusion is a technique in Additive Manufacturing where a laser or electron beam is utilized to melt and bond material, crafting a three-dimensional part [23]. This method in (**Fig 2.2**) encompasses several popular printing technologies, such as Multi Jet Fusion (MJF), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM), and Selective Laser Sintering (SLS).

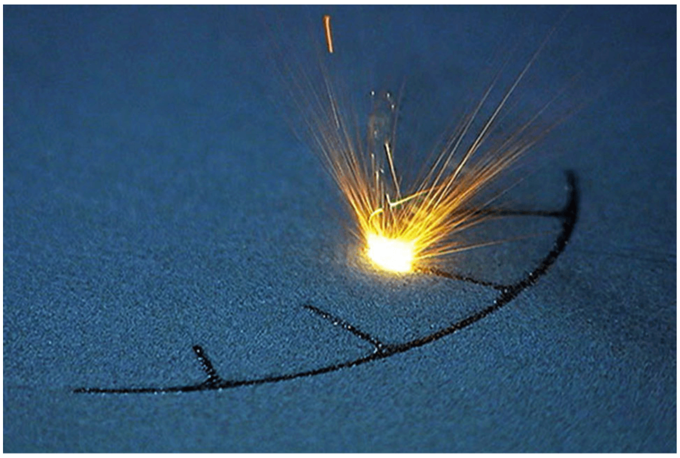

Figure 2.2. Laser powder Bed Fusion(source:LaserPowderbedfusion)

2.1.3 Binder Jetting

Binder Jetting involves the precise placement of a bonding agent, which is a type of binding, into a powder material to construct a three dimensional object as shown in (**Fig 2.3**). Uniquely, this method distinguishes itself from other Additive Manufacturing techniques by not utilizing heat to meld the material, setting it apart in the field of 3D printing technologies.

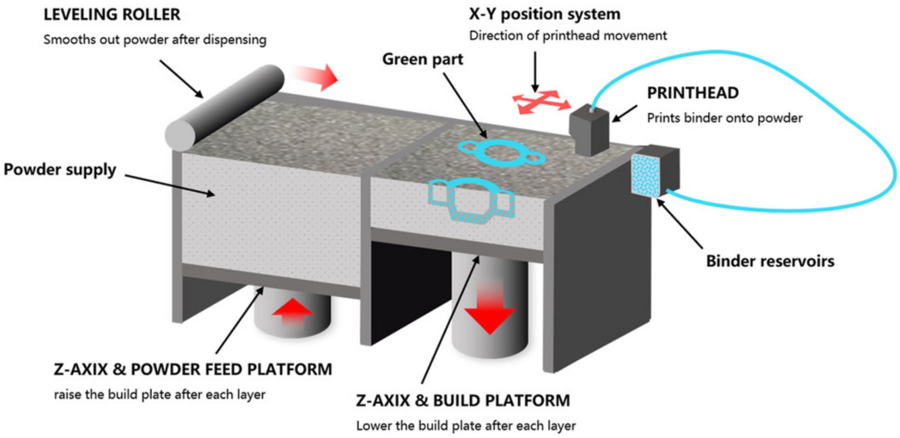

Figure 2.3. Binder Jetting (Source:Binder Jetting)

2.1.4 Material Jetting

Material Jetting operates by precisely ejecting droplets of construction material, as outlined by ISO/ASTM (2021). This technique involves the targeted placement of material droplets, adding them layer upon layer into the build platform,(**Fig 2.4**) resulting in the creation of a three dimensional component.

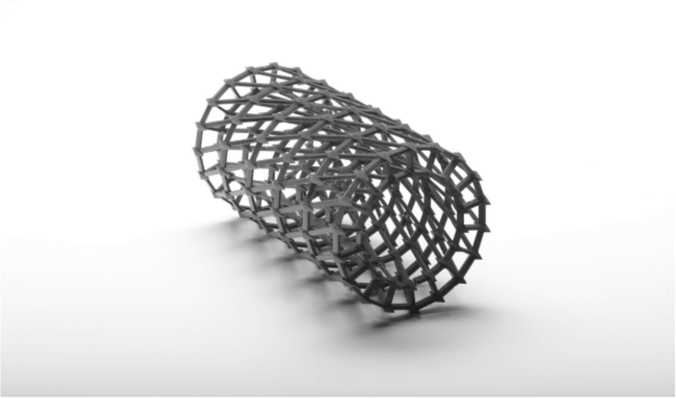

Figure 2.4. Material Jetting

2.1.5 Directed Energy Deposition

Directed Energy Deposition technology works by directing intense heat(**Fig 2.5**), like that from a laser, electron beam, or plasma arc, to melt materials as they are layered on each other, forming a three dimensional object. This method closely resembles the welding process but is executed with much finer precision, allowing for detailed 3D creations [72].

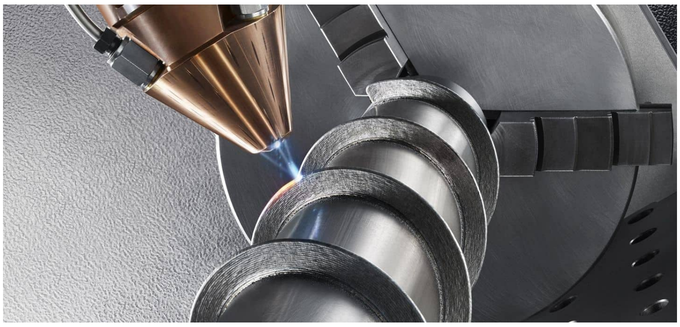

Figure 2.5. Directed Energy Deposition(source:D.E Deposition)

2.1.6 Sheet Lamination

According to ISO/ASTM 52900-2015, this technique involves constructing a three dimensional object through the accumulation and lamination of slim material sheets(**Fig 2.6**). The sheets are united using methods such as bonding, ultrasonic welding, or brazing, and the desired form is refined through laser cutting or CNC machining.

Figure 2.6. sheet Lamination

2.1.7 Material extrusion

Material extrusion is a method in additive manufacturing that builds three dimensional objects by using a filament of thermoplastic or composite material [40] as shown in **Fig 2.7**. The process involves pushing the filament through a heated nozzle, melting it, and then systematically layering it on a build platform to form the 3D object.

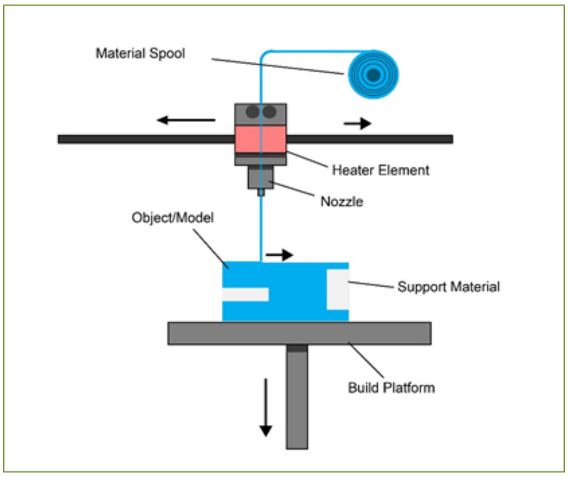

Figure 2.7. Material Extrusion(source:Material E. process)

2.2 Additive Manufacturing Processes

The additive manufacturing (AM) journey transitions from digital CAD models to tangible components, with applications varying by product complexity and development stage [29]. Simpler items may utilize AM for prototyping, while intricate, engineering heavy products benefit from AM throughout various design iterations. Initially, Additive Manufacturing (AM) can quickly produce basic prototypes; however, as the development advances, parts often require meticulous finishing, including smoothing and painting, to meet final specifications. This adaptability in creating complex shapes without traditional tooling underlines AM's value across the product lifecycle. The process typically unfolds through eight key stages (**Fig 2.8**), starting from digital modeling in CAD, followed by conversion to a universally accepted STL format for AM machines, highlighting the foundational steps for building parts using AM technologies.

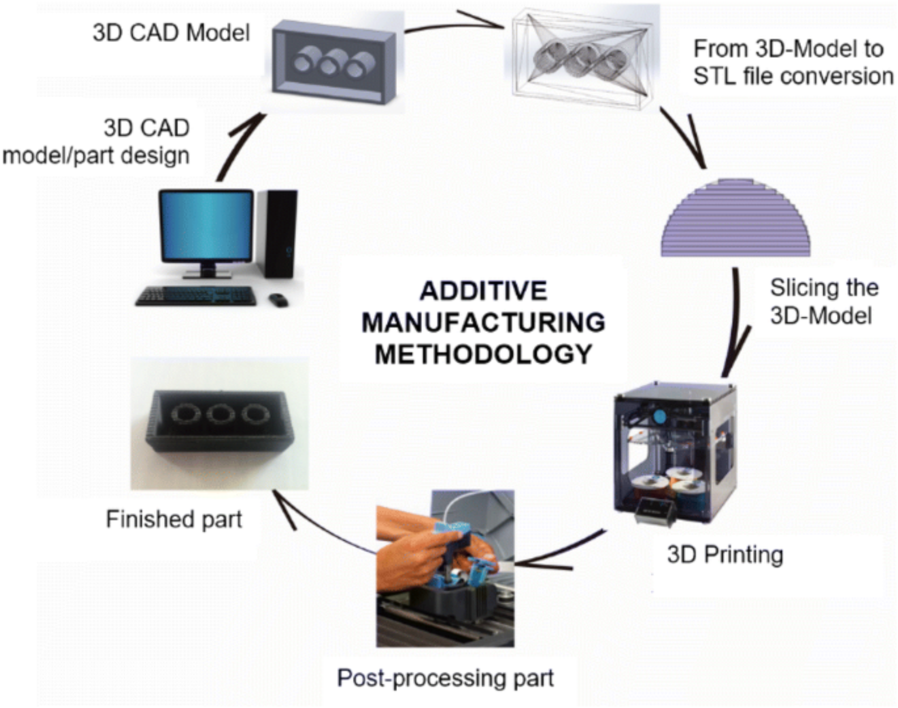

Figure 2.8. Process of AM from CAD to final Product (source:AM Processes)

- **Computer Aided Design (CAD):** Every piece created through additive manufacturing begins with a digital blueprint that accurately captures the object's shape and dimensions. This digital model is typically crafted using sophisticated CAD software, capable of rendering detailed 3D solids or surface visuals. Additionally, methods like laser scanning or optical scanning can be employed to generate these digital representations, especially useful for reverse engineering existing objects into their digital counterparts.

- **Conversion to STL:**The STL format is widely accepted by additive manufacturing devices as a standard, with most CAD platforms capable of generating this type of file. This format captures the outer surfaces of a CAD-created model, serving as the foundation for slicing the model into layers for the printing process.
- **Transfer SLT file Manupulation to AM machine:**The STL file, which outlines the part's dimensions, needs to be uploaded onto the AM device [49]. At this stage, adjustments might be necessary to ensure its dimensions, positioning, and alignment are optimized for the manufacturing process.
- **Machine SetUp:**Before starting the printing process, it's crucial to correctly configure the AM device. This preparation involves adjusting various parameters, such as the type of material being used, the energy source specifications, the thickness of each printed layer, and the overall timing for the build, to ensure optimal printing conditions.
- **3D Printing :**Fabricating the component is predominantly automated, allowing the machine to operate with minimal oversight. It is necessary, however, to perform occasional checks to ensure the process runs smoothly, guarding against issues such as material shortages, power failures, or software malfunctions. [70]
- **Removal:**After the additive manufacturing process is complete, the newly printed objects need to be carefully extracted from the machine. [6] This step often involves specific interactions with the machine, which might include safety mechanisms designed to ensure conditions, such as temperature, are safe for handling, and that the machine's parts have ceased movement, to prevent accidents.
- **Post Processing:**After being taken out of the machine, the components often need further cleaning to be fully prepared for application. [4] At this stage, the pieces might be fragile or attached to support structures that require removal. This step usually demands patient and skilled manual work to ensure the parts are properly finished without causing damage.
- **Finished /Application:**After removal from the printing machine, the components might be in a state where they can be directly utilized. Nevertheless, there could be a need for further processing to meet usage standards. This might include applying a primer and paint to achieve a desired surface texture and appearance. [3] Such finishing processes can be extensive and time-consuming, especially for specifications that demand high quality finishes. Additionally, assembly with other mechanical or electronic parts may be necessary to complete the final product or model.

As we covered the various phases of the AM process, it is crucial to acknowledge the need for meticulous maintenance of AM equipment. These devices, often incorporating delicate laser or printing technologies, demand regular oversight to function optimally, particularly in environments free from dust and noise. Despite being designed for autonomous operation, incorporating routine inspections into the maintenance regime is essential, as different machines and technologies have unique maintenance requirements.

2.3 Advantages and limitations of Additive Manufacturing

Additive Manufacturing (AM) is revolutionizing the way we approach production, especially in sectors requiring high levels of customization and precision, like healthcare. The technology's ability to create intricate designs without the extra cost is a game changer. This "complexity for free" enables the production of customized medical devices, implants, and models that perfectly match the unique requirements of individual patients, something that was previously either very expensive or impossible [6].

One of the standout benefits of AM is its contribution to sustainability through reduced waste. [59] Traditional manufacturing methods often involve subtracting material from a larger block, inevitably leading to significant waste. In contrast, AM adds material only where it's needed, layer by layer, minimizing excess. [3] This efficiency is not just about conserving materials but also about reducing the environmental impact of production processes.

Rapid prototyping is another area where AM shines, allowing healthcare professionals to quickly turn new ideas into tangible prototypes. This speed is crucial for innovation in medical treatments and devices, as it allows for fast iterations and optimization based on real world testing and feedback. [70] Additionally, AM simplifies the supply chain, making it possible to produce parts on demand and on site, which can be particularly valuable in remote or resource limited settings where traditional supply chains may be slow or unreliable.

Additive Manufacturing's ability to work with a wide range of materials, including those compatible with the human body, opens up new possibilities for medical applications. [20] It supports the creation of lightweight yet durable structures that can lead to more comfortable and effective medical devices and implants.

2.3.1 Limitations of Additive Manufacturing

Despite these above significant advantages, AM faces some challenges. The speed of production can be a limitation, especially for large or complex parts, which may not be suitable for emergency situations requiring rapid mass production. [5] The initial investment in AM technology and materials can also be high, posing a barrier to its adoption in contexts where cost-efficiency is paramount.

Precision and accuracy are critical especially in medical applications, and while AM continues to advance, achieving the necessary standards can sometimes be challenging. [70] The range of materials suitable for medical use is also limited, with specific requirements for biocompatibility and mechanical properties that not all AM materials meet. The technical expertise required to operate AM equipment and prepare models for printing can be a hurdle, requiring significant training and knowledge. [4]

AM offers transformative potential for the healthcare sector,Aerospace,Mechanical,and beyond, promising unprecedented levels of customization, efficiency, and innovation. [5,70] However, realizing this potential fully requires addressing the current limitations around speed, cost, accuracy, material selection, and ease of use.

As the technology continues to evolve, it is likely that these challenges will diminish, making AM an even more integral part of future manufacturing landscapes.

Chapter 3

Short term Production Planning and Scheduling of Additive Manufacturing

Short term production planning is crucial,this approach is a tailored strategy designed to optimize the efficiency and effectiveness of Additive Manufacturing (AM) operations, addressing the unique challenges and leveraging the opportunities presented by AM technologies. [40] It involves a systematic use of resources, including energy, machinery and materials, aiming to streamline production schedules and minimize costs.

The operations of an Additive Manufacturing (AM) job usually comprise the following three steps: preparation, production, and collection [43].

Preparation includes creating a digital model with CAD and converting it to an STL file, which is then transferred to the AM machine and set up for printing. [29]

Production involves the automated 3D printing process, where the machine builds the object layer by layer, requiring minimal oversight but occasional checks.

Collectionencompasses the removal of the printed object from the machine, followed by post-processing steps such as cleaning, finishing, and assembly to meet final specifications. [29]

Efficient planning and scheduling for short term production in Additive Manufacturing (AM) are Important components of modern manufacturing strategies.They are vital for meeting the dynamic and adaptable needs of the market [21].

In additive manufacturing (AM), production planning is crucial for optimizing efficiency and meeting production targets. Strategies are categorized into improving printed qualities, saving materials/time, and achieving objective printed properties. [32] Improving printed qualities involves optimizing layer thickness, print parameters, and post-processing to enhance precision and surface finish. Saving materials and time includes build orientation adjustments, and efficient path planning to reduce waste and print duration. Achieving objective printed properties requires selecting appropriate materials, adjusting infill patterns, and controlling environmental conditions to ensure desired strength and durability. [33] These strategies collectively enhance AM production efficiency and output quality.

These scheduling frameworks, coupled with heuristic part placement methods, aim to optimize the utilization of AM resources, thereby minimizing cycle times and reducing instances of order lateness. Such strategic scheduling is instrumental in enhancing the throughput and reliability of AM production operations, ensuring that projects progress smoothly and within the expected timelines.

The complexities of additive manufacturing processes require the use of advanced technological tools for effective short-term production planning and scheduling to enhance planning and optimization.

The application of Iterative Optimization based Simulation (IOS) models, which join the capabilities of simulation engines with computational platforms like MATLAB, exemplifies this approach [44]. These models offer a robust mechanism for assessing the impacts of various scheduling policies on the production outcome, enabling a data driven approach to decision making.

The use of genetic algorithms for exploring optimal part configurations and arrangements enhances the planning process. Through leveraging these advanced computational techniques, manufacturers can analyze numerous scheduling and part placement possibilities, Pointing the most efficient pathways to production, this elevates the decision making process to a more strategic level.

Additive Manufacturing (AM) also presents a unique set of challenges that demand a multi disciplinary optimization strategy. Critical issues such as bin packing, nesting, job shop scheduling and addressing constraint satisfaction are most important for the effective and efficient allocation of parts to machines [43]. The task of nesting, which involves the strategic arrangement of parts within a build chamber to prevent overlap, requires meticulous attention.

This consideration is important for maximizing build space usage, minimizing support material need, and reducing the effort needed in post processing [33]. Addressing these challenges head on is essential for leveraging the full potential of AM technologies, ensuring that each part is produced with the optimum orientation and configuration.

Effective short term production planning in AM, encompasses an interdisciplinary approach that carefully evaluates part design, material properties, and the specific capabilities of AM technologies. [19]

The relationship between scheduling policies and part nesting within the build chamber is vital. It plays a critical role in optimizing build times, ensuring part quality, and enhancing the overall performance of the AM production system. The strategic application of simulation models and genetic algorithms empowers manufacturers to navigate the complexities of Additive Manufacturing production with informed confidence, fostering productivity and operational agility.

The landscape of short term production planning and scheduling in AM is marked by a continuous evolution of strategies and methodologies, driven by advancements in technology and manufacturing practices [24]. Embracing these developments is imperative for manufacturers aiming to maintain a competitive edge in an increasingly dynamic market. [16] By adopting a comprehensive and nuanced approach to production planning, manufacturers can achieve greater efficiencies, foster innovation, and respond adeptly to the changing demands of the industry, marking a significant stride towards the future of manufacturing.

3.1 Principles of Short Term production Planning in AM

Principles of short term production planning in Additive Manufacturing (AM) combine a detailed approach that include cost management,health and safety considerations, quality assurance,customization,minimal environment impact,supply chain reconfiguration and product customization [56,75].These principles are elemental to leveraging Additive Manufacturing's unique capabilities and overcoming its limitations, thereby optimizing production efficiency, product quality, and societal benefits.

- **Customization and Personalization**

  Additive Manufacturing (AM) strength lies in the abilities to facilitate high level of personalization, customization and without significantly impact timelines or production costs [75]. This principle is significant in short term production planning, especially in the sectors like healthcare, where personalized medical devices and implants are in demand [28]. It underlines the need for flexible production systems adept at quickly adapting to individual design specification.

- **Efficient Material Use and Environmental Sustainability**

  Additive Manufacturing is recognized for its material efficiency, constructing objects layer upon layer with minimal waste. In production planning, this shows the strategies aimed at maximizing material use and reducing waste [28]. This principle contribute to sustainability goals, including the use of bio compatible or recyclable materials, significantly reducing the environmental footprint of manufacturing activities.

- **Rapid Prototyping and Testing**

  - **Layered Complexity Management**

    Unlike traditional manufacturing methods that often require simpler designs to accommodate manufacturing constraints, Additive Manufacturing allows for the production of complex geometries without additional cost [74]. Production planning in AM includes the principle of layered complexity management, which involves strategizing the build process to optimize the construction of complex features, such as internal channels and complex structures, which are costly to achieve through conventional methods.

- **Digital Inventory and On Demand Manufacturing**
  Additive Manufacturing supports the concept of a digital inventory, where physical stocks are replaced by digital files that can be printed as needed [76]. This principle significantly reduces the need for physical storage space and associated costs while allowing for more flexible and responsive production cycles. On demand manufacturing is useful in industries and it aligns closely with just in time manufacturing strategies to reduce waste and improve cash flow.

- **Technological Integration and Automation**
  Integrating AM with digital technologies like CAD, CAM, and AI streamlines production planning, enabling rapid design to production cycles, enhancing quality control, and facilitating predictive maintenance of AM equipment [8]. This integration is important for optimizing process efficiency and product quality.

- **Cost Management**
  Effective cost management is a cornerstone of AM production planning, focusing on optimizing resource allocation and minimizing waste to control production costs. [55] This includes strategic decisions on material selection, process optimization, and energy consumption, ensuring cost effective production without compromising quality [8].

- **Quality Assurance**
  Quality assurance in AM involves meticulous planning to ensure that the final products meet predetermined standards and specifications [74, 76]. This includes implementing robust quality control measures throughout the production process, from design validation to post processing inspections, ensuring that products consistently meet high quality standards.

Short term production planning in Additive Manufacturing integrates several key principles, from customization to quality assurance, to fully leverage AM's advantages while addressing its challenges. By strategically applying these principles, organizations can achieve greater production agility, cost efficiency, and superior product quality, contributing to environmental sustainability and enhanced societal well being.

3.1.1 Planning constraints and requirements of AM

The planning constraints and requirements of Additive Manufacturing (AM) involve multiple dimensions, including technological considerations, cost estimation, and the integration of design and manufacturing constraints. [61] This overview synthesizes information focusing on key aspects related to structural optimization, cost considerations, and the design for AM (DfAM) principles [11].

Technological and Design Constraints

1. Design for Additive Manufacturing (DfAM): DfAM prioritize the integration of manufacturing capabilities and constraints early in the design process [11]. This approach is important for AM, where the only capabilities of AM technologies such as creating complex geometries can be fully supported only if considered during the design phase. DfAM involves considering aspects like the orientation of the part during printing, support structure minimization, and the optimization of material usage to achieve the desired mechanical properties and geometrical accuracy.

2. Machining Constraints Integration: Coordinating machining constraints into the AM configuration process is fundamental, particularly for metal Additive Manufacturing parts that require present cycle machining on accomplish the vital surface completion or layered precision. [31] This incorporates considering the powers applied during the machining system and the requirement for extra material to oblige machining recompenses. The combination of these imperatives can fundamentally impact the plan, expecting the adjustments to guarantee that the AM part can be safely fixtured and effectively machined without undermining its integrity.

Cost Considerations

1. Cost Modelling Techniques: Cost estimation for AM involves different variety of models and techniques, reflecting the multifaceted nature of AM processes. These models may include considerations for machine operation,the cost of materials,post processing and any required machining. Activity Based Costing (ABC) is one approach mentioned for accurately attributing the costs associated with each stage of the AM process, enabling more precise estimation of the total manufacturing costs [17].

2. Economic Aspects of AM: AM offers the potential for cost savings in specific applications, particularly where the complexity of parts does not significantly add to the cost, unlike traditional manufacturing methods. [53] Athough, the economic advantages of AM must be carefully weighed against factors such as slower production rates for some technologies, the higher costs of AM materials, and the need for post processing. [1] These factors can impact the overall cost effectiveness of AM, making thorough cost analysis essential for decision making. [1, 53]

Integration of Constraints and Requirements

The combination of both design and cost constraints into the AM process is critical for optimizing the technology's potential benefits. This integration requires a holistic approach that considers the entire lifecycle of the manufactured part, from design through post processing, including machining and finishing operations [69]. By addressing these constraints and requirements comprehensively, AM can be effectively utilized to produce parts that meet or exceed performance criteria while also being cost effective.

The importance of integrating design considerations,technological capabilities, and cost estimation techniques from the early stages of the manufacturing process. This approach ensures that AM can be effectively applied to produce optimized, functional parts that meet specific application requirements.

3.2 Role of Short Term Production Planning in AM

Short-term production planning, particularly scheduling, is important in AM due to its significant impact on operational efficiency, customer satisfaction, and resource management. [15] Strategic capacity planning is essential in the manufacturing industry, the principles and methodologies of short-term scheduling are particularly applicable and adaptable to AM.

Scheduling in AM involves the complex coordination of various fabrication processes. The layer-by-layer nature of AM adds to the overall complexity, demanding a detailed understanding of the entire production sequence [25]. Effective scheduling in AM requires meticulous planning concerning the order and timing of each step to ensure smooth workflow and high-quality outputs.

The dynamic nature of the AM field, characterized by rapid technological and product evolution, demands a flexible approach to scheduling. This adaptability is crucial for quickly incorporating new materials, processes, and designs into production schedules, ensuring that innovation and customer requirements are consistently met.

Lead times and high costs present additional challenges for AM scheduling. AM operations often face significant lead times for material procurement and machine setup. [23] Coupled with the high costs of AM materials and machinery, strategic scheduling becomes essential. It aims to optimize resource use and minimize costs by thoughtfully planning each production phase. [46]

The fluctuations in demand and capacity in additive manufacturing resemble the unpredictability experienced in the semiconductor industry. Given the unpredictable demand for AM products, scheduling must incorporate strategies that offer flexibility in production capacity. [75] This flexibility ensures that fluctuating demand is met effectively without compromising efficiency or increasing waste.

Various literature review highlights the transformative role of scheduling in AM, showing how AM technologies are reshaping manufacturing strategies, enhancing efficiency, and enabling unprecedented customization. [6,60] AM enhances production by integrating and simplifying processes, allowing for the consolidation of production steps into a cohesive and streamlined workflow. This capability reduces the complexity traditionally associated with routing, loading, and scheduling activities. [34]

AM supports a high degree of customization and flexibility in scheduling. Operations such as inspection, reporting, production dispatching, and corrective actions can be more effectively tailored to specific product demands. [34] The direct manufacturing of parts from CAD files simplifies the scheduling process, making it more agile and responsive to changes.

Digitalization plays an imprtant role in AM scheduling, shifting complexity to the systems digital components rather than the operational processes. [72] This shift necessitates the development of new practices for production dispatching, inspection, and reporting, leading to a digitalized manufacturing landscape where physical and digital processes are closely linked.

Capacity planning in AM shows the strategic nature of scheduling decisions concerning machine selection, investment, and AM technology adoption. These decisions, influenced by economic, technological, and market considerations, highlight AM's comprehensive impact on scheduling and production planning. [5] Managing risks and uncertainties in AM involves addressing demand variability, resource availability, and technological progression. [68] A scheduling methodology that integrates these factors into the production planning process facilitates more informed strategic decision making.

3.3 Challenges of Scheduling in Additive Manufacturing

Scheduling in Additive Manufacturing (AM) encloses a complex interplay of factors, demanding detailed planning and optimization to meet production goals efficiently. This complexity is primarily due to the fundamentals characteristics of AM processes and the unique demands of the AM production environment. [4]

The challenges can be dissected into two main areas: technological constraints and optimization of production planning. Each of these areas encompasses several critical factors that influence the scheduling process.

Technological Constraints

- **Material and Process Selection:**

  One of the foundational challenges in AM scheduling is the selection of appropriate materials and processes. Each Additive Manufacturing process, be it multi Jet fusion, powder based laser technologies has specific requirements and challenges regarding the materials it can use effectively.

  The choice of material and process affects not just only the quality and characteristics of the finished product but also the production time [3]. Different materials may have varying melting points, requiring adjustments in the printing parameters that can significantly impact the overall production schedule.

- **Part Geometry and Orientation:** The geometry of the parts to be produced plays an important role in scheduling. Complex geometries might necessitate support structures or specific orientations to ensure the quality of the print, which can increase the production time [74].

  Determining the optimal build orientation is a non trivial task that seeks to balance between minimizing support usage, ensuring structural integrity, and reducing printing time [59]. This challenge is exacerbated in the production of customized or non standard parts, where each piece may require individual assessment and orientation planning.

Optimization of Production Planning

- **Cycle Time Reduction:** Reducing the cycle time, which encompasses build time, setup time, and post processing time, is a primary objective in AM scheduling [59]. This requires a comprehensive approach that optimizes each step of the production process, from build orientation and nesting to the efficient allocation of parts across multiple machines. Achieving a reduction in cycle time enhances productivity and allows for quicker response to customer demands.

- **Maximizing Machine Utilization:**

  Optimal scheduling aims to decrease production times while maximizing the efficiency of AM machines [46]. This requires distributing tasks among machines to evenly balance the workload and reduce downtime.

- **Adapting to Mass Customization:** Additive Manufacturing is particularly suited to customized production due to its flexibility.This advantage also introduces scheduling challenges, as the production plan must accommodate a wide variety of part designs and customer specifications. [59]

  The scheduling system must be dynamic, able to adjust to changes in the order queue and handle the complexities of producing a mix of standardized and customized parts within the same production run.

- **Integration with Existing Systems:** Integrating AM scheduling solutions with existing manufacturing systems, including design software, material management systems, and post processing facilities, is crucial for a seamless production flow [46]. This integration must ensure that scheduling decisions are informed by accurate, up to date information from across the production ecosystem.

Scheduling in AM involves navigating a multidimensional challenge space, where technological constraints intersect with the need for sophisticated production planning and optimization strategies.These multidimensional challenges requires a deep understanding of AM technologies, innovative algorithmic solutions, and a holistic view of the production environment.

3.4 Literature Review of Scheduling Problems and Solution Methods in Additive Manufacturing

Additive Manufacturing (AM) is revolutionizing traditional manufacturing by enabling the production of complex geometries and customized parts directly from digital models. [70] However, this flexibility and customization come with unique scheduling challenges.

The intricate interplay between machine capabilities, material availability, part geometries, and the dynamic nature of AM processes require advanced scheduling strategies tailored specifically to the AM environment. [29]

3.4.1 Scheduling Problems in Additive Manufacturing

The scheduling of AM processes presents unique complexities compared to conventional manufacturing. Traditional scheduling methods often fail to address the dynamic nature of AM, where factors like machine capabilities, material availability, and part geometries play crucial roles. [31] Key scheduling problems in AM.

- **Job Sequencing:** Determining the order in which jobs are processed, considering job priorities, due dates, and specific requirements of each job such as material type and mechanical properties. [47]

- **Machine Allocation:**Assigning jobs to specific AM machines based on their capabilities, such as material compatibility, build volume, and printing speed, to optimize equipment use. [73]

- **Batch Processing:** Grouping multiple parts into a single build job to maximize build space utilization and efficiency. [73] This involves the strategic placement of parts to minimize support material use and post-processing time.

- **Maintenance Planning:** Scheduling regular maintenance for AM equipment to maintain operational efficiency and prevent unexpected breakdowns, which can cause production delays. [20]

- **Material Management:** Ensuring materials are available and properly allocated to scheduled jobs, considering factors like material type, color, and specific properties required for the job. [17]

- **Post-Processing Scheduling:** Allocating time for necessary post-processing steps, such as support removal, curing, and surface finishing, which are critical for achieving the desired quality and functionality of the printed parts. [57]

3.4.2 Solution Methods for Scheduling in Additive Manufacturing

To address the scheduling challenges in AM, several advanced methods and approaches through literature review have been addressed.

- **Optimization Techniques:** Various optimization methods, including linear programming, mixed-integer programming, and constraint programming, have been applied to solve scheduling problems in AM. These techniques aim to optimize key performance metrics such as lead time, throughput, and energy consumption.

- **Heuristic and Metaheuristic Algorithms:** Heuristic methods like genetic algorithms, simulated annealing, and tabu search are employed to find near-optimal solutions for complex scheduling problems in AM. [22] These algorithms are particularly useful for dealing with large and complex problem spaces where exact methods are computationally infeasible.

- **Artificial Intelligence and Machine Learning:** AI and ML techniques are increasingly being used to improve scheduling in AM. These methods can predict machine failures, optimize part placement, and dynamically adjust schedules based on real-time data. [38] For example, reinforcement learning can be used to develop adaptive scheduling policies that respond to changing conditions in the production environment.

- **Integrated Scheduling Systems:**The integration of automation and robotics with scheduling systems can enhance the efficiency of AM operations. [7] Advanced scheduling systems that incorporate real-time monitoring and control capabilities can dynamically adjust schedules to account for machine status, material availability, and other factors.

3.5 Scheduling strategies in Additive Manufacturing

Scheduling strategy in additive manufacturing (AM) is comprehensive and touches upon several critical aspects that differentiate Additive Manufacturing (AM) from traditional manufacturing processes. [23] It underlines how the unique features of AM such as design freedom, the ability to produce complex geometries, and the feasibility of on demand production necessitate distinct approaches to scheduling.

1. Understanding Additive Manufacturing's Impact on Scheduling

The construction of layer by layer inherent in AM allows for the direct realization of parts from digital models, which introduces variability in production times. Unlike traditional manufacturing, where production times can often be predicted more linearly based on quantity, AM production times vary significantly with the complexity of the part being produced [35].

This requires a scheduling system that is adaptable and can accurately predict production time based on part complexity, material used, and the specific AM technology deployed. Advanced simulation tools and predictive models may play an Important role in forecasting production timelines accurately.

2. Design Strategies Affecting Scheduling

- **Manufacturing Driven Strategy:**

  Manufacturing Driven Strategy: A Manufacturing Driven Strategy is an approach to production that focuses on optimizing manufacturing processes by leveraging both Additive Manufacturing (AM) and traditional manufacturing methods [37].

  The central concept is to adjust dynamically allocate resources and adjust schedules based on real-time analysis of efficiency, cost, and throughput requirements. [55] This strategy emphasizes flexibility, allowing manufacturers to switch between AM and traditional methods as needed to maximize productivity and cost-effectiveness. It ensures that the production process is adaptable and responsive to changing conditions, such as fluctuations in demand or variations in material availability.

- **Function Driven Strategy:**

  Function Driven Strategy in AM focus AM's design capabilities to create intricate, high functionality parts, requiring longer production times and specialized post processing [72]. This complexity demands robust scheduling systems to optimize machine usage and minimize bottlenecks. Advanced scheduling algorithms and real time adjustments are essential to handle the variable production and post processing duration [54]. Efficient management of these complexities ensures manufacturers can fully utilize AMâs potential, delivering high functionality parts without delays.

3. Role of Workforce Development in Scheduling

A knowledgeable and skilled workforce is crucial in minimizing production errors and rework, which in turn, improves scheduling accuracy and efficiency [19]. Training programs that focus on Additive Manufacturing's specific skills can significantly enhance the effectiveness of scheduling strategies by ensuring that the workforce can anticipate and mitigate issues that may arise during production, leading to more reliable and predictable scheduling.

4. Technology Integration for Efficient Scheduling

The integration of digital tools and technologies plays a vital role in enhancing scheduling efficiency. Utilizing CAD software, AM file preparation tools, and production management systems enables accurate production time estimation, resource allocation, and real time monitoring of AM processes. This integration is critical for creating a responsive and adaptable scheduling system that can handle the complexities of AM production.

Understanding AM's Innovation System: The AM innovation system is characterized by its interconnectivity and the interactions between various actors (e.g., reasrch labs,firms, universities,firms) who utilize AM technologies [39]. This system is influenced by market conditions, technological opportunities, and government policies, which all play a significant role in shaping the direction and efficiency of AM processes, including scheduling.

5. Customization and On Demand Production's Impact on Scheduling

Additive Manufacturing (AM)'s strength in producing customized parts and small batch sizes on demand introduces a level of variability that traditional scheduling systems are not equipped to handle efficiently [35]. To accommodate this, scheduling strategies must be highly flexible and capable of rapidly responding to changes in demand. This may involve the use of sophisticated planning tools that can update production schedules in real time and leverage predictive analytics to forecast demand patterns.

Efficient scheduling in AM is not just about allocating resources and timing; it is about integrating a deep understanding of AM technologies, design strategies, workforce capabilities, and the latest digital tools to create a flexible, responsive, and efficient production workflow. As Additive Manufacturing continues to evolve and find new applications, scheduling strategies will also need to adapt, embracing new technologies and methodologies to tackle Additive Manufacturing (AM)'s full potential for innovative manufacturing.

Chapter 4

Technological Innovations and Their Impact on AM Production Planning

The rapid evolution of technology has significantly impacted additive manufacturing (AM), particularly in production planning and scheduling. [24] Technological innovations, such as artificial intelligence (AI) and machine learning (ML), have introduced new paradigms that enhance the efficiency, accuracy, and flexibility of AM processes. [27] These evolutions have transformed AM from a prototyping tool to a robust production technology capable of manufacturing end use parts across various industries, including aerospace, medical, and automotive sectors.

The integration of AI in AM allows for real time monitoring and adaptive control of the production process, ensuring high quality standards, reducing waste, and enabling predictive maintenance to minimize downtime and enhance productivity. [9]

Machine learning models have been effectively in optimizing process parameters. By leveraging historical data and applying sophisticated processes, these models predict the optimal settings for various AM processes, such as laser power, scan speed, and layer thickness. [51] This predictive capability not only improves the quality of the final product but also reduces the need for extensive trial and error experiments, thus saving time and resources.

The data analytics play a crucial role in enhancing AM production planning by analyzing large datasets generated during the AM process. [27, 51] These insights enable continuous improvement in production strategies, leading to more efficient and cost effective operations.

The implementation of decentralized AM production systems, facilitated by advanced technologies, offers significant logistical advantages. [27, 60] Technological innovations have profoundly impacted AM production planning by introducing advanced tools and methodologies that optimize scheduling, enhance quality control, and improve overall efficiency.

4.1 Advance Software for Production planning

In production scheduling for Additive Manufacturing (AM), the importance of sophisticated software tools is paramount in managing the complex and changing requirements of AM processes. This detailed examination delves into how these tools enhance scheduling efficiency in Additive Manufacturing.

4.1.1 Integration of STEP-NC and Scheduling in AM

STEP-NC (STandard for the Exchange of Product model data - Numerical Control) is a CNC programming standard designed to replace the traditional G-code. [71] Developed by the International Standards Organization (ISO) as ISO 14649 and ISO 10303 AP-238, STEP-NC extends the original STEP (ISO 10303) standard to include data models specifically for numerical control.

STEP-NC address the limitations of G-code by offering a comprehensive data model that ensures seamless integration across the entire CAD/CAM/CNC digital chain. [62] This eliminates the need for post-processing and allows for intelligent CNC machine control.

4.1.2 Capabilities of STEP-NC in Process Planning for Additive Manufacturing

STEP-NC offers several advanced capabilities that significantly enhance process planning in additive manufacturing (AM).

- **High-Level Data Representation**
  STEP-NC provides a detailed and high-level representation of manufacturing information, including geometric data, material properties, and process parameters. [14] This comprehensive data model supports precise planning and execution of additive manufacturing tasks. By capturing detailed descriptions of layer geometries and toolpaths, STEP-NC ensures high accuracy and complexity in AM processes.

- **Seamless Integration**
  STEP-NC enables seamless integration across different stages of the manufacturing process, from design (CAD) through manufacturing (CAM) to control (CNC). This is particularly beneficial for additive manufacturing, where iterative adjustments and refinements are often necessary. The bidirectional data

flow facilitated by STEP-NC ensures that any design changes are automatically reflected in the manufacturing process, eliminating the need for manual updates.

- **Error Minimization**

  Traditional additive manufacturing processes often suffer from errors due to approximations in geometric representations, such as STL files. [50] STEP-NC minimizes these errors by using precise geometric data models, ensuring higher accuracy in the final product. [62] This precision is crucial for maintaining the quality and functionality of manufactured parts, especially those requiring high tolerances and complex geometries.

- **Hybrid Manufacturing Support**

  STEP-NC supports the integration of additive and subtractive manufacturing processes. This capability is essential for hybrid manufacturing environments where parts may need to be built using AM and then refined using traditional machining methods. [52] By providing a unified platform for planning and executing these combined processes, STEP-NC enhances overall manufacturing flexibility and efficiency.

- **Advanced Process Planning and Automation**

  STEP-NC enables sophisticated process planning by incorporating high-level data about the manufacturing process, including toolpath optimization and process parameters. [14] This allows for the creation of optimized and adaptive manufacturing plans that can adjust in real-time based on feedback and changing conditions. The automation capabilities of STEP-NC reduce the need for manual intervention, increase efficiency, and ensure consistent quality across production runs.

4.1.3 Applications of STEP-NC in Process Planning for Additive Manufacturing

- **Intelligent Process Planning**

  STEP-NC enables detailed and intelligent process planning for additive manufacturing. [62] By utilizing high-level data representation, including precise geometric data, material properties, and process parameters, it allows for comprehensive planning and control of AM processes. [50] This ensures optimal layer deposition, material usage, and overall build quality, leading to higher precision and efficiency in manufacturing.

- **Integration of Additive and Subtractive Processes**

  One of the key applications of STEP-NC in AM is its ability to seamlessly integrate additive and subtractive manufacturing processes. [52] This hybrid approach allows parts to be initially built using additive manufacturing and subsequently refined or finished using traditional subtractive methods such as milling or turning.

  This integration is managed within a single STEP-NC program, enhancing manufacturing flexibility and efficiency by combining the strengths of both processes.

- **Real-Time Adjustments and Optimization**
  The advanced process planning capabilities of STEP-NC allow for real-time adjustments and optimization during the manufacturing process. [2] This is particularly useful in AM, where conditions can change rapidly, and immediate adjustments may be necessary to ensure optimal results. STEP-NC supports the integration of feedback loops and quality checks directly into the process plan, allowing manufacturers to adjust parameters in real-time based on actual production data.

STEP-NC plays a foundational role in AM by providing a framework that enables the precise and intelligent scheduling of manufacturing operations [71]. By facilitating the detailed representation of geometric data in part programs, as shown in (**Fig 4.1**) STEP-NC allows for more efficient scheduling by automating the derivation of machining paths and sequences.

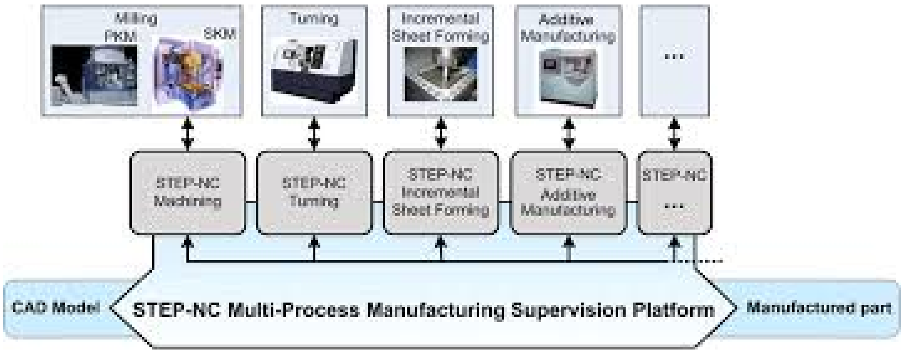

Figure 4.1. STEP NC Compliant Process Planning of AM(source:STEP NC

This capability is particularly valuable in remanufacturing, where the need for accurate and quick turnaround of parts is critical. By reducing errors across the entire CAD-CAM-CNC chain, STEP-NC enhances the scheduling process, ensuring that parts are produced within acceptable time frames and with fewer iterations or corrections.

Dynamic Scheduling with Cyber-Physical Systems:

The concept of the smart factory, underpinned by cyber-physical systems, significantly influences scheduling in Additive Manufacturing (AM). (**Fig 4.2**) shows how The systems provide a seamless flow of information between machines, products, and operators, allowing for real time adjustments to production schedules based on current data and conditions.

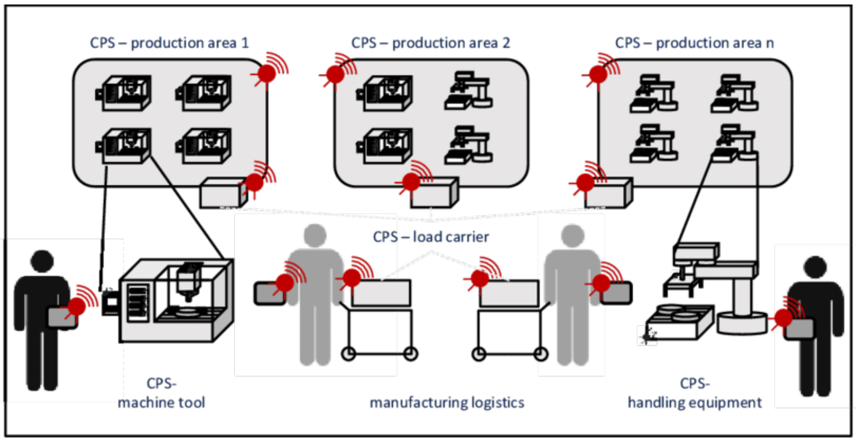

Figure 4.2. Dynamic Cyber Physical Production Systems(source:Cyber Phisical Production

This dynamic scheduling capability is essential in AM, where production scenarios can change rapidly due to variations in material properties, machine availability, or design modifications. Software tools that leverage these systems can preemptively adjust schedules, allocate resources more effectively, and respond to disruptions without significant downtime, thus maintaining continuous production flow [67].

Optimization Through Multiple-Process Planning:

Software tools that enable the integration of multiple manufacturing processes including both additive and subtractive methods greatly enhance the flexibility and efficiency of AM scheduling, as detailed in (**Fig 4.3**).

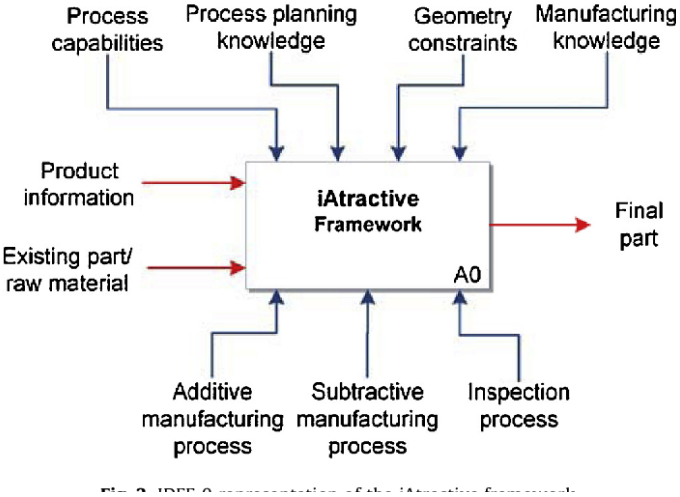

Figure 4.3. Optimization Through Multiple Process Planning (source:Process planning for AM

These tools analyze and determine the optimal sequence of operations, taking into account the specific requirements and constraints of each process [64]. For instance, a part may initially built using an additive process but requires milling for fine surface finishes. Software that can schedule these integrated processes ensures that each step is timed perfectly to optimize the throughput and minimize the waiting times between processes.

Geometric Reasoning for Accurate and Efficient Scheduling:

Advanced geometric reasoning capabilities within AM software tools play a crucial role in scheduling. These tools analyze geometric data to ensure that manufacturing processes adhere to specified tolerances and that the final geometry of manufactured parts meets design specifications [60]. By predicting potential issues in part geometries early in the production cycle, these tools can adjust schedules proactively, reducing the need for rework or additional processing steps. This not only saves time but also enhances the overall efficiency and output of the manufacturing process.

Production scheduling in Additive Manufacturing is a complex task that benefits significantly from specialized software tools. These tools integrate sophisticated data handling, dynamic scheduling capabilities, and intelligent process planning to ensure that manufacturing operations are efficient, timely, and flexible [60]. By leveraging technologies such as STEP-NC, cyber-physical systems, multiple process integration, and geometric reasoning, these software solutions provide manufacturers with the ability to optimize their production schedules, adapt to changes swiftly, and maintain high standards of quality and efficiency. This leads to a more streamlined Additive Manufacturing(AM) process, capable of meeting the exacting demands of modern manufacturing sectors.

4.2 Integration of Automation and Robotics in scheduling

Integrating automation and robotics into scheduling, particularly in advanced manufacturing processes such as Additive Manufacturing (AM), significantly enhances efficiency and precision. This approach allows for precise control over the manufacturing processes, improving both the speed and quality of production.

Automation ensures consistent material deposition, important for building complex components with high accuracy, while robotics provides the flexibility to execute sophisticated, non planar layer constructions [20]. These technologies collectively streamline the scheduling and execution of manufacturing tasks, enabling more complex designs and better utilization of materials.

This integration is particularly effective in optimizing production workflows and improving the adaptability of manufacturing systems to new materials and geometric challenges.

4.2.1 Integration of Automation and Robotics with Scheduling Systems

In additive manufacturing (AM), the Interaction between robotitcs,automation, and advanced scheduling systems significantly Increase production efficiency.

Automation primarily governs the operational parameters of the manufacturing process, ensuring precise control over aspects like material flow, speed, and cooling rates with minimal human intervention [10]. Robotics complements this by providing the physical execution capabilities necessary for tasks such as cutting,welding, or layering materials, enabling a highly efficient, consistent, and quality controlled production environment.

A critical aspect of integrating robotics into Additive Manufacturing (AM) involves sophisticated task allocation and motion scheduling. Task allocation assigns specific operations to robots based on their location,capabilities, and availability, ensuring that each robot performs tasks it is optimally suited for.Simultaneously, motion scheduling plans the sequence and paths that robots follow to execute their tasks efficiently and without interference from other robots [12]. This component is important for avoiding collisions and ensuring that all tasks are completed in the most time efficient manner possible.

The fundamental of these operations is powered by advanced scheduling systems. These systems employ algorithms and mathematical models based on constraint programming to dynamically manage task assignments and schedules [36]. They are particularly adept at handling the complexities of a variable and large scale workspace, robots, and a diverse range of tasks. By continuously assessing the workspace and adjusting schedules in real time, these systems optimize workflow and adapt to changes swiftly and efficiently.

Collision avoidance is another essential feature in these integrated systems. It ensures that robots operate in a synchronized form within the same space without crossing paths in a disruptive way. This include intricate spatial and temporal planning to maximize the use of available space and ensure safety without compromising the speed of operations.

The systems designed for Additive Manufacturing (AM) are scalable and adaptable, capable of accommodating increases in production volume and complexity without needing significant modifications [65]. This adaptability is important in manufacturing environments subject to rapid shifts in demand or production parameters, allowing processes to adjust quickly to new requirements or unforeseen challenges.

The integration of automation, robotics, and scheduling systems in additive manufacturing not only streamlines production but also enhances the flexibility and scalability of manufacturing processes. This integration results in reduced production times, decreased costs, and improved product quality, aligning modern manufacturing with innovative production capabilities.

4.3 Role of AI and Machine Learning in AM

Additive Manufacturing (AM) is coping with a transformation, gratitude to innovative approaches brought by artificial intelligence (AI) and machine learning (ML). These technologies are leading to a more efficient, adaptable, and scalable production process, with AI and ML driving some changes in production planning.

AI and AM Collaboration:

The combination of Artificial Intelligence and AM permit innovative production methods. This combination allows for greater customization and flexibility in manufacturing [27]. Applications range from robotics to bioengineering, where AI is used to create complex geometries and smart structures. These intelligent systems incorporate smart materials that respond to various motive,streamlining production and reducing Costs.

Design Optimization and Customization:

Artificial Intelligence(AI) help design optimization in AM, leading to improved customization. With AI driven techniques like support vector machines(SVM) and hierarchical clustering, manufacturers can tailor product designs to specific needs [51]. This flexibility enables companies to quickly respond to customer demands, giving them a competitive advantage. By optimizing design, production processes become more efficient and adaptable.

Process Optimization and Quality Control:

Artificial Intelligence (AI) and Machine Learning (ML) play an important role in optimizing AM processes. Techniques like artificial neural networks and supervised learning help identify key relationships between process parameters and outcomes, allowing manufacturers to enhance quality and efficiency [27]. AI also contributes to quality control by monitoring product quality, detecting defects, and predicting characteristics like surface roughness and porosity. This leads to a more consistent production of high quality products.

Artificial Intelligence(AI) and Machine Learning(ML) are reshaping AM by offering innovative tools for process optimization, quality control, and design customization. This transformation signifies a major leap forward in manufacturing, presenting new possibilities for a more efficient and flexible production process [8].

4.3.1 Optimization Techniques of AI and ML in Scheduling Tasks of AM

The integration of artificial intelligence (AI) and machine learning (ML) in Additive Manufacturing (AM) has opened up new lines for refining scheduling tasks.

Traditional methods such as Finite Element Method (FEM) and advanced machine learning models are combined to enhance the process parameters for Powder Bed Fusion (PBF) in AM [9]. This unique approach not only reduces the need for extensive physical experiments but also ensures better control over the quality of the final products.

Machine learning plays an important role in predicting and optimizing process parameters, allowing manufacturers to refine elements like laser Power,temperature, and scan speed to achieve the desired mechanical properties. With ML, is possible to simulate and forecast how these factors affect the end result, helping to minimize defects and improve the overall efficiency of the production process.

Data-driven approach has transformed how manufacturers approach process optimization. By analyzing large sets of data, AI and ML can reveal trends and patterns that guide adjustments to scheduling and other critical tasks in AM [38]. This capability to derive insights from extensive data collection makes it possible to refine the scheduling processes to achieve optimal performance.

An important benefit of AI-driven insights in AM is the capacity to reduce variability in the manufacturing process, which leads to more consistent, high quality outputs. This consistency is essential for industries that rely on precision, such as aerospace and healthcare. AI and ML ensure that each component produced meets strict quality standards, paving the way for broader adoption of AM technologies [38].

The combination of AI and ML in AM scheduling offers a powerful toolset for improving process efficiency, improving product quality, and reducing production costs. With these these technologies, manufacturers can make more informed decisions that contribute to a smoother, more reliable production flow [9, 38].

4.3.2 Challenge of AI and AM Integration

Although the integration of Artificial Intelligence (AI) and Additive Manufacturing (AM) offers many benefits, challenges remain. Data sharing, cyber physical security, and integrating human elements into manufacturing require careful consideration [45]. Addressing these issues involves creating secure data sharing mechanisms, ensuring cyber physical security, and incorporating human interaction through augmented reality (AR) and virtual reality (VR). These challenges also present opportunities for innovation and development in Artificial Intelligennce(AI) driven AM systems.

4.4 Real Time Scheduling and Monitoring in additive manufacturing

Real-time scheduling and monitoring in additive manufacturing (AM) support advanced technologies to ensure efficient production, consistent product ,reduce down time and quality.

Different technologies,as well as the Industrial Machine Learning (ML), Internet of Things (IIoT), Acoustic Emission (AE) monitoring, and Machine Learning (ML), work together to provide continuous data acquisition and immediate feedback for rapid adjustments. [8]

- The Industrial Internet of Things (IIoT) plays an important role in real time scheduling and monitoring by showing a network of interconnected devices and sensors throughout the manufacturing process [63].Sensors collect data on critical parameters like pressure,humidity, temperature, and vibration, transmitting this information in real-time to a centralized monitoring system. This setup allows operators to inspect the AM process, detecting any outliers as they occur and enabling quick adjustments to maintain production quality.

- IIoT sensors provide a steady flow of data, offering a comprehensive view of the manufacturing environment.constant data stream enables immediate detection of deviations from expected conditions, facilitating real time adjustments and enhancing quality control [63].The data collected by IIoT can be analyzed to predict when equipment maintenance is needed. This predictive maintenance approach helps reduce unexpected downtime by allowing proactive interventions, ensuring the manufacturing process runs smoothly and efficiently.

- Acoustic Emission (AE) monitoring includes detecting sound waves produced during the AM process. Acoustic Emission (AE) sensors can identify unique acoustic signals related to specific events such as melting,delamination, solidification,and cracking. When integrate with Machine Learning, these signals can be analyzed to determine patterns that indicate potential defects or quality issues [48].

  This technology provides real time quality monitoring without affecting the manufacturing process, allowing operators to identify critical events and take corrective action to prevent defects.

- Acoustic Emission (AE) monitoring also offers improved process control. By analyzing acoustic signals in real-time, manufacturers can gain deeper insights into the manufacturing process, enabling better control and reducing the occurrence of defects. This leads to enhanced overall product quality and a more consistent production process [48].

- Machine Learning (ML) plays a crucial role in improving real time scheduling and monitoring through advanced data analysis and pattern recognition [26].

  ML algorithms can process large volumes of data collected by IIoT and AE sensors, extracting meaningful insights that guide real time adjustments and predictive maintenance. This approach to predictive analytics helps reduce downtime by identifying when equipment needs maintenance or when process adjustments are required.

ML also improves quality assurance by allowing early detection of quality issues. By classifying acoustic signals and other data, ML facilitates a proactive approach to quality control, reducing the need for post-production inspections and rework.

Real-time scheduling and monitoring in additive manufacturing depend on a combination of advanced technologies to ensure efficient production and consistent product quality. IIoT provides continuous data acquisition, AE monitoring offers real-time quality insights, and ML enables predictive analytics.

These technologies enable manufacturers to respond quickly to changes, predict maintenance needs, and maintain high-quality standards, ultimately leading to a more efficient and effective AM process.

Chapter 5

Conclusion

This thesis has explored the important challenges and innovative solutions related to scheduling in additive manufacturing (AM). Through literature review, it has been established that AM presents unique scheduling difficulties that traditional methods fail to address effectively. These challenges include the selection of materials and processes, the complexity of part geometries, and the integration with existing manufacturing systems. The demand for customization and the variability in production times add layers of complexity to AM scheduling.

To tackle these challenges, the thesis has focused on several advanced scheduling methodologies. Key among these is the integration of principles from optimization and operations research, which provide strong frameworks for improving scheduling efficiency. Additionally, the incorporation of automation and robotics into scheduling processes has shown significant promise in enhancing productivity and reducing lead times. Real-time monitoring and adaptive scheduling systems, powered by advancements in AI and machine learning, offer dynamic and flexible solutions that can respond to the ever-changing demands of AM environments.

The literature emphasize the necessity for novel scheduling strategies that utilize advanced algorithms, real-time data processing, and seamless integration of automation technologies. These strategies are critical for optimizing key performance metrics such as lead time, throughput, and energy consumption. Moreover, the adoption of sophisticated software tools and cyber-physical systems enables precise production time estimation and resource allocation, ensuring that manufacturing processes are both efficient and adaptable.

In conclusion, the advancement of scheduling methodologies tailored specifically to AM is essintial for its successful integration into mainstream manufacturing. By addressing the unique challenges of AM, these innovative scheduling strategies can enhance productivity, reduce costs, and accelerate the time-to-market for AM-produced components. This Thesis literature review contributes to the broader understanding of how to effectively manage AM production, supporting its potential to revolutionize modern manufacturing through greater agility, customization, and sustainability.

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