



Dissertation

*Can manufacturing companies compete in this technological revolution
without implementing the MBD process?*

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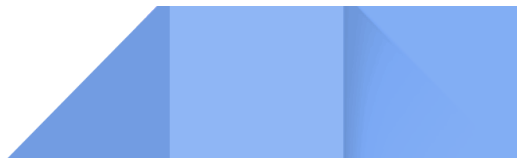
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Abstract

The transformation of 2D drawings to model-based definition (MBD) is a critical aspect of engineering and manufacturing processes in modern industries. This paper explores the evolution of this transformation and its impact on the efficiency and accuracy of product development. This paper provides a comprehensive overview of the challenges, benefits, and best practices associated with adopting MBD in engineering and manufacturing companies by examining reliable sources such as academic journals, industry publications, and case studies. Additionally, the paper highlights the role of digital technologies and standards in facilitating the transition from 2D drawings to MBD and discusses the implications for future advancements in this area. This paper offers valuable insights for engineering and manufacturing practitioners, researchers, and educators through a systematic analysis and documentation of the findings.

While 3D models play a significant role in modern manufacturing, it is crucial to acknowledge that geometric and dimensional tolerances remain a vital aspect of the production process, especially in high-precision assemblies. Altering these tolerances could adversely affect the production process and the final product. The advent of Industry 4.0 has granted manufacturing industries access to remarkable technological breakthroughs. Nevertheless, numerous companies have yet to capitalise on these innovations to stay competitive and keep pace with the market leaders. This study aims to compare the competitiveness of manufacturing companies that rely on traditional drawings with those that have adopted Model-Based Definition (MBD) technology. This research aims to provide insights into the advantages and limitations of using MBD in the manufacturing industry by analysing two case studies. The study of two cases will help understand if manufacturing companies must remain competitive with using drawings, compared to companies that have already implemented the use of MBD.

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List of abbreviations

Abbreviation	Definition
DWG	Cad drawing file
FEA	Finite elements analysis
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
MBD	Model based definition
AM	Additive Manufacturing
PLM	Product Lifecycle Management
HO	heterogeneous Object
CATs	Computer-aided technologies
RP	Rapid Prototype
CDR	Critical design review
CPS	Cyber-Physical System
WF	Workflow
CI	Continuous Improvement
DDR	Detail Design Review
DMU	Digital Mock-Up
BOM	Bill of Materials
MBM	Model base manufacturing
KPI	Key performance indicator
IoT	Internet of things
AI	Artificial intelligence
GD	Generative design
PMI	Product manufacturing information

INTRODUCTION

1 Introduction

1.1 Introduction

The manufacturing sector is making tremendous strides with the help of digital transformation, as Industry 4.0 technologies are being widely adopted across the globe. These revolutionary technologies can bring about significant changes across various industries. According to a report from Markets and Markets, the current market share of Industry 4.0 is valued at over USD 71.7 billion and is projected to exceed USD 150 billion by 2024, (Ammar, Haleem et al. 2021). Integrating advanced technologies in manufacturing has led to a growing awareness of sustainable manufacturing practices. Sustainable manufacturing involves utilising innovative processes and systems that enable the production of high-quality products and services using sustainable resources while prioritising the safety of employees, customers, and surrounding communities. Moreover, it entails mitigating environmental and social impacts throughout the entire life cycle of the product or service, (Machado, Winroth et al. 2020).

The manufacturing industry has undergone a significant transformation from mass production carried out by humans to the introduction of machines. Today, we witness an unprecedented advancement where shop floors are solely operated by autonomous robots, simulations of products, materials, and processes, as well as cutting-edge technologies such as augmented reality, additive manufacturing, Internet of Things (IoT), Cybersecurity, Cloud, and AI (Artificial Intelligence), (Bai, Dallasega et al. 2020). The subject of this positive revolution in manufacturing companies has been brought up due to the lack of similar progress in the approval and validation process of new products through traditional 2D drawings. According to (Gherghina, Tutunea et al. 2017), CAD models have been fully integrated into workstations across various manufacturing companies since 1981, and there have been few advancements since then. Hence, the motivation behind this study and the question, *Can manufacturing companies compete in this technological revolution without implementing the MBD process?*.

Engineering drawing is a type of technical drawing used to fully and clearly define requirements for engineered items. It visually represents an object or structure and includes details such as dimensions, materials, and manufacturing methods. Engineering drawing is an essential communication tool for designers and engineers, (Scheibel, Mangler et al.

2021). The extensive use of technical drawings throughout the entire manufacturing process of a product or assembly is indisputable. Therefore, it is imperative to study the history and evolution of technical drawings from their inception to the present day. This study aims to provide a comprehensive understanding of the subject matter.

Additionally, this research will explore the development and progress of 3D designs in the manufacturing industry to understand how they have transformed the manufacturing process. It will not forget how important it is to keep all the work developed in the design department connected with the manufacturing processes and other departments of the company.

Effective Product Life Cycle Management (PLM) is a crucial business process that enables companies to manage every aspect of their product's life cycle effectively, from conception to disposal. This process involves several stages: product design, development, manufacturing, marketing, and sales. Implementing PLM helps businesses streamline operations, reduce costs, improve product quality, and ultimately enhance customer satisfaction. Utilising PLM tools, companies can easily manage their product data, collaborate with their teams, and make informed decisions based on real-time information, (Bokinge, Malmqvist 2012).

The upcoming study will delve into the design processes and drawings released by manufacturing companies in the aeronautical sector. Through analysing two case studies and a comprehensive literature review, the author aims to understand the advantages and disadvantages of the processes currently employed by many companies in this industry. This will provide valuable insights into the sector's workings and aid in the identification of areas for improvement.

At the end of the discussion, the relationship between the drawing process and new technologies like MBD (Model-Based Definition), AM (Additive Manufacturing), and GD (Generative Design) will be analysed to gain a deeper understanding of their interconnections.

1.2 Aims

- Find whether or not companies that do not want to introduce the MBD (model-based definition) as the most suitable channel to deliver detailed parts to manufacturing in the coming years would have considerable difficulties in being competitive.
- Evaluating the most commonly used 2D drawings by manufacturing companies.
- Assessing the 3D CAD evolution into the manufacturing industry.
- Analysing two case studies from aerospace manufacturing companies.
- Assessing new technologies and their implications with drawings.

1.3 Objectives

- To evaluate the 2D drawing process and its implication in the current technological Industry 4.0 revolution.
- To explore drawing history evolution.
- To identify and evaluate factors from collected data impacting the two case studies.
- To propose recommendations to manufacturing companies based on research findings.
- To assess MBD, AM & GD capabilities and its benefits in the manufacturing industry.

1.4 Justification

The evolution of CNC programs and machines in the manufacturing industry has led to significant advances in control and quality, resulting in increased productivity through intelligent production, adequate inventory control, and real-time product traceability. However, despite these technological advancements, many companies still utilise traditional drawing processes in their design and manufacturing operations, which have been used for over forty years. While some entities have embraced new methodologies in this field, most still adhere to traditional practices.

To address this issue, this paper aims to evaluate the two types of processes to determine which one is more compatible with the industry's technological changes. By comparing traditional and modern processes, this analysis seeks to identify the benefits and drawbacks of each approach and determine which one is more appropriate in the current manufacturing landscape.

1.5 Methodology

Although a systematic literature review was not conducted, the researcher opted for a comprehensive method to gather information on what other researchers have done regarding the paper's topic. This approach allowed for the collection of a wider range of evidence and findings from books, case studies, and scientific articles.

In addition, the researcher conducted two quantitative case studies on distinct manufacturing companies to analyse statistically the design processes and the release of drawings in their respective projects. These case studies provided valuable insights into the practical aspects of the topic under investigation and helped complement the literature review findings.

LITERATURE REVIEW

2 DRAWINGS

2.1 2D Drawings

Throughout history, humans have used various communication forms to convey their ideas and creations. From prehistoric drawings and carvings of animals and humans to modern-day drawings, sketches, and documents, graphic communication has played a crucial role in the development and distribution of information. While early forms of visual representation did not necessarily meet the standards of formal drawings, they served as essential tools for conveying ideas and concepts. Architects and inventors have long relied on sketches and drawings to guide the creation of their tools, crafts, and structures. However, the production process was often more akin to art than engineering, creating unique and highly individualised items. Despite the evolution of modern technology and the rise of standardised production methods, the art of graphic communication remains an essential part of human creativity and innovation.

Several lines of research (Wildgen 2004), present that tools made of stone, bone, ivory, wood, and clay have been created since the time of Homo erectus to start with the long history of drawings. These objects are considered transportable art pieces and belong to profane life rather than ritual or sacred contexts. The artistic forms found are mainly decorative or representational. Decorative forms are typically geometrical, whereas representational forms imply the shape of an existing object. In many cases, they are both. At this stage, we can distinguish between self-referential form-giving, such as in ornamentation, and iconic art, which uses realistic contours and colours perceived in external objects and animals. However, the human body or groups of people are still represented in this art. From the beginning, there is a trend towards abstraction on one side and towards mimesis on the other, which points to two fundamental dimensions of semiotic activity.

An engraved bone may serve as a prototype or a model of imitation (*figure 1*), which orients further perception of similar objects. It is also an object of value that can be given, stolen, inherited, or buried with the owner. Becoming an object of value marks the point of transition to ritual and magical objects. The stability of the sign form attracts other meanings. It helps to organise a whole field of mythical or religious knowledge, which existed as a belief or behavioural schema before the time-permanent sign was endowed with its meaning. Hence, the system of beliefs and practices becomes psychologically sizable with the help of permanent signs.

The technique of engravings on objects may be extrapolated to architecture as Palaeolithic huts were built with big bones, wood and coats. If the group lived in caves or "abris" or used them as ritual places, the walls could bear engravings or be sculptured. The first technique was used until Neolithic times and is still practised by tribes in Australia.

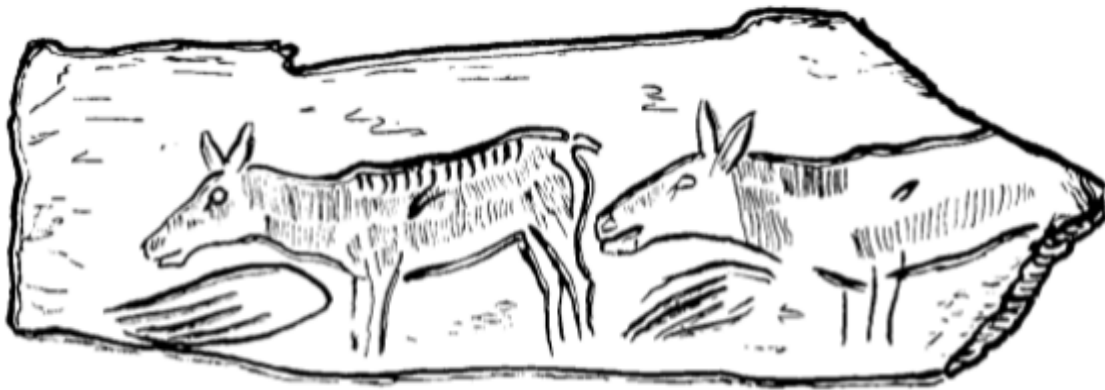


Figure 1. Bones of mammoth figural engravings on a bone from the cave Chaffaud (France, cf Rhotert 1956).

One of the fascinating capabilities of the human mind is its ability to create vivid mental images and translate them into art. Unlike any other species, humans possess the talent to visualise the unseen and bring it to life through drawing. This incredible skill is a testament to the extraordinary power of our imagination and artistic expression. In several industries and organisations, the art of drawing is frequently relegated to a secondary position, often stored away in a cabinet or dark room. This perspective needs to appreciate the actual value and significance of drawings, which bring to life new and innovative ideas and solutions that would otherwise remain abstract concepts. Drawing can make these ideas tangible and easily understood, allowing them to be shared and further developed (Mills 2010).

Creating art is akin to engaging in a conversation, as it facilitates the expression of ideas and concepts. This process of transforming the thought into a visual form is considered crucial.

When a designer begins to draw, his thoughts are connected with the pen to follow a path with results full of creativity. This phenomenon can be likened to a creative "shortcut," enabling the swift generation of ideas. A thorough understanding of the connection between the mind and the hand is critical to any artistic pursuit, as it provides a deeper comprehension of the creative process (Migayrou, Migayrou et al. 2016). Much like verbal language is constructed from words, idioms, phonemes, and syntax to form complete sentences; visual language also utilises shapes, forms, lines, textures, and colours in

combination with graphic rules or structures to create symbols, icons, or images. Anyone can acquire and hone this visual vocabulary through learning and practice. After successfully producing the first image, subsequent ones can be developed with increasing skill and continued practice (Whitson 2019).

Visual communication is an art form that uses principles and rules previously agreed upon. As drawing styles evolve, the principles of visual communication also change. Skilled artists may modify these principles while they draw, but never arbitrarily. Instead, they do so to convey their subject matter effectively. The structural principles on which a drawing is founded are critical to understanding the artist's or designer's intentions. While familiarity with a particular artist's style may help, more is needed to comprehend every drawing style. To engage in effective communication with an artist, one must first learn and understand their principles (Rawson 2016).

2.2 Evolution of 2D drawings

Different drawing styles have emerged throughout history based on people's beliefs, traditions, and practices.

For instance, in ancient Egypt, drawing was used to decorate tombs and tell stories of the pharaohs' lives. The Egyptians used hieroglyphics and pictorial writing to convey various messages through drawings. Similarly, in mediaeval Europe, the art of drawing was heavily influenced by the Church. Many artists were commissioned to create religious artworks that depicted biblical scenes and figures. These artworks were used to educate the public about the teachings of the Church and inspire devotion (Migayrou, Migayrou et al. 2016).

After exploring the origins and different types of drawings, it is worth noting that technical drawings are fundamental to the manufacturing industry. These drawings communicate a wide range of information about a product or component, including dimensions, materials, and manufacturing processes. They are typically produced using computer-aided design (CAD) software and are essential for ensuring a product can be manufactured to the required specifications. Technical drawings also play a crucial role in quality control, allowing manufacturers to verify that a finished product meets the required standards. In short, technical drawings are a vital tool for ensuring the efficient production of high-quality goods. In the modern era, drawing has continued to evolve with the advent of technology and new artistic styles. Today, there are various forms of drawing, including pencil, charcoal, digital, and many others.

Leonardo da Vinci (1452–1519), the great painter, sculptor and inventor of the Renaissance period, left behind a vast collection of sketches that exemplify his exceptional imagination and scientific precision. These sketches cover various interests, from architecture and engineering to biology, physiology, anatomy, astrology, hydraulics, and aeronautics. Da Vinci's insatiable curiosity led him to explore the internal anatomy of the human body by dissecting cadavers, resulting in detailed drawings that remain relevant to this day. He also studied the flight patterns of birds and insects to apply his knowledge to aerodynamic devices. Furthermore, Da Vinci also recorded the design of different manual parts, tools and mechanisms that were useful to aid progress (figure 2).

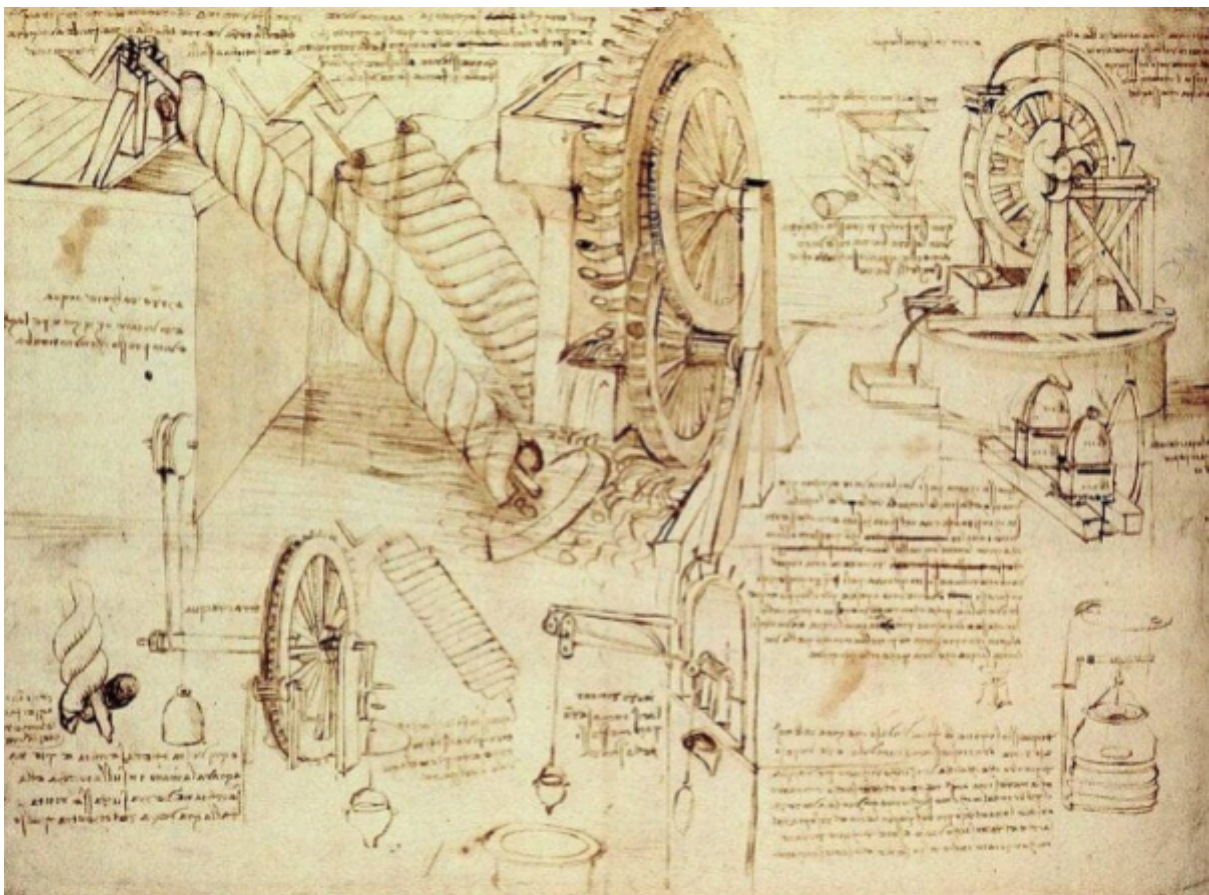


Figure 2. Water Lifting Devices, (Da Vinci).

However, engineering professionals have long relied on the abstract and unchanging principles of Monge's descriptive geometry in applying technical drawing to their work. This singular column of scientific basis is essential for graphical representation and enables professionals to communicate with one another through the use of orthogonal projections that accurately depict 3D components within their respective domains of activity. Gaspar Monge, a noteworthy figure in the French Revolution, was a mathematician, physicist, and

engineer who made significant contributions to the field of descriptive geometry. His writings formed the foundation of the current Technical Drawing, a necessary language for engineers and artisans. In 1795, Monge introduced the new science of descriptive geometry with two primary goals: accurately representing three-dimensional objects on two-dimensional drawings and enabling precise descriptions of bodies about their shape and position.

After that, Alfredo Bensaude became the first director of the Instituto Superior Técnico (IST) at the University of Lisbon. He established the first national technical school of engineering in Portugal, based on international standards at the time. Bensaude introduced Technical Drawing as an essential subject for future engineers to facilitate effective communication and analysis of engineering projects. His contributions to engineering education and modern teaching methods have had a lasting impact on the field, making IST one of the leading engineering schools in Europe today (A. Z. Sampaio 2018).

According to (Simmons III 2021), drawing is a fundamental part of our world, although it often goes unnoticed. When most people think of drawing, they tend to picture fine art and illustrations found in books, magazines, cartoons, graphic novels, animations, or video games. However, these visible forms of drawing are just the spike of the iceberg. After almost every piece of art or artefact it can be admired today, a series of drawings is hidden away in large museums or companies worldwide. Whether it is a beautiful piece of furniture, sculpture, engraving, or painting, it all began with quick sketches to define the details. Without drawing, there would be no civilization as we know it today. Modern society has developed with the importance of using technical drawings, as they are essential in creating everything from buildings and bridges to cars and other technologies that make industrial and post-industrial societies possible.

With the advent of computer technology in drawing, the once-dominant hand gestures for drawing lines have now been relegated to the background. In their place, pressing keys, clicking buttons, and moving mice take centre stage. As a result, drawing a line is now a task handled by algorithms that translate user input to its corresponding visual representation in the design process. However, this shift has brought about two significant consequences. Firstly, there is now a temporal and mechanical gap between the designer and the visual representation of the drawing on the pixel array. This gap is because the line is no longer drawn directly by the designer's hand but rather by the algorithm interpreting their input. Secondly, the author has little control over the physical appearance of the line once it is drawn, as the pixels on a monitor or printer change colours to provide a digital approximation of the line. This means that the designer cannot easily change the line's physical properties,

such as thickness or texture, after it has been created based on what needs to be achieved on determined final products (Migayrou, Migayrou et al. 2016).

2.3 Engineering Drawings

Engineering drawing is considered the standard language in engineering and architecture. It is creating drawings in a specific format that effectively communicates information about the design intent. Unlike decorative or artistic paintings, engineering drawings do not allow any interpretation, and they represent a specific element in a way that the viewer quickly understands without any misinterpretation (figure 4). The terms engineering drawing, drawing, mechanical drawing, technical drawing, and technical drawing are interchangeable. Drawing is a precise and universal language that employs lines, symbols, and annotations to convey information about objects, whether for construction or manufacturing purposes. It is a crucial tool utilised across various technical disciplines such as architecture, civil and electrical engineering, electronics, piping, manufacturing, and structural engineering. The term mechanical drawing can be interpreted in various ways. In the manufacturing industry, it refers to mechanical stretching, which is named after the mechanisms involved. In the construction industry, on the other hand, mechanical drawing pertains to creating diagrams for heating, ventilation, and air conditioning (HVAC) systems, which are the mechanical aspects of architectural projects (Madsen, Madsen 2017).

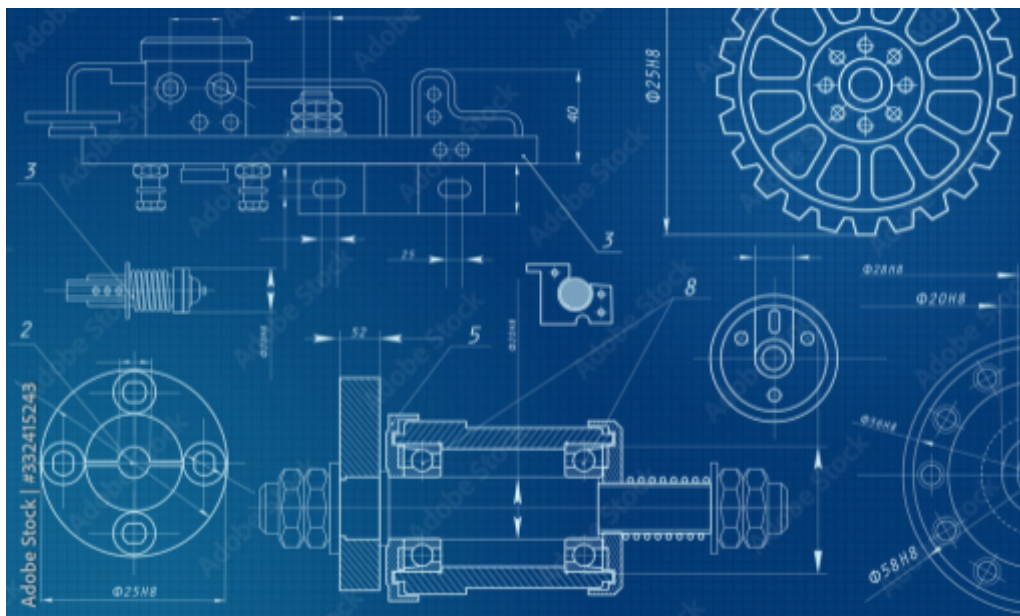


Figure 3. Mechanical engineering drawing on blue background. Sectioning objects with holes, ribs.

Technical drawing. (is1003).

In the modern world of commerce, it is not uncommon for a product to be conceptualised in one country, produced in another, and put together in a third. The manufacturing and assembly process relies on detailed engineering drawings governed by national and international standards and codes of practice. The most rigorous standards are international, which enables businesses to compete on a global scale. The International Organization for Standardization (ISO) sets these international standards, many of which relate to engineering drawings. This is because the information contained within a drawing is complex and must be accurately conveyed to ensure a successful outcome. It is worth noting that the information in an engineering drawing is legally binding and forms the basis of the agreement between a contractor and subcontractor. ISO standards rely heavily on symbology to ensure these standards transcend language barriers. Companies can maintain productivity by accurately transferring information from the engineering design phase to the manufacturing and assembly phases. While referred to as "Graphic Communications" in some literature, the more contemporary term used by ISO is "Technical Product Documentation" (TPD). This comprehensive term encompasses all aspects of design communication, as there are now various means of defining the necessary information for product manufacturing beyond traditional paper drawings. TPD's full name is 'Methodology, presentation and verification of specification product techniques'. It includes the methodology for design execution, geometric product specification, graphical representation (engineering drawings, diagrams, and three-dimensional modelling), verification (precision metrology and measurement), technical documentation, electronic formats and controls, and related tools and equipment (Griffiths 2002).

3. 3D Models

3.1 Definition of 3D Models

A 3D model is a type of information that accurately defines the exterior and interior of an object. With the "fullness" of information in a solid model, a computer can quickly produce a line image with no hidden lines, (Xu, Xun 2009). There are two primary methods for modelling solids. Firstly, designers can specify points, curves, and surfaces to define the mathematical representation of boundary surfaces. After, they can then knit these surfaces together to create a finite volume of the object. Alternatively, designers can choose simple shapes like blocks or cylinders with specific dimensions, positions, and orientations. These shapes can be combined using logic operations such as union, intersection, and difference. The final representation generated by either of these methods is a complete and detailed digital approximation of the object or an assembly of parts, (Bi, Wang 2020b).

Using 3D CAD (Computer Aided Design) tools has significantly expedited time-to-market and minimised product development expenses. Over the past few decades, the extensive acceptance of 3D CAD technology has led to the transformation of product development from physical to digital mockup and from 2D to 3D design, (Ye, Liu et al. 2008). Emerging technologies can improve our methods of achieving new and old processes. Thanks to the widespread adoption of CAD technology, its usage has expanded beyond visualisation, communication, and documentation. CAD technology now offers numerous benefits, including correction and reversibility of operations, standardisation that reduces manufacturing costs, optimization of material configurations, analysis and simulation for product working and mould flow, better coherence and connectivity for design teams, rapid prototyping and manufacturing, computer-aided manufacturing, reverse engineering, tutorials and explanatory animations for product usage, and documentation and archival of designs throughout the entire design process, (Rama Murthy, Mani 2012).

3.2 Evolution of 3D Models

The designer can effectively create designs that are both innovative and practical. Visualising and integrating are essential in the creative process, allowing the designer to explore different possibilities and consider how each element will work together, (Beitz, Pahl et al. 1996). (Bi, Wang 2020a) shows an advancement of the 3D models by presenting Computer-aided technologies (CATs) as software tools and systems that assist in various

product development and manufacturing stages. CATs can design, analyse, and simulate products and production systems and plan, schedule, and control their operations. These technologies help optimise the performance of products and production processes, reduce costs, and improve overall efficiency. By leveraging the power of CATs, companies can streamline their design and manufacturing workflows, minimise errors, and achieve faster time-to-market.

The development of Computer Aided Engineering (CAE) was deemed necessary to facilitate the integration of locally sourced material compositions into 3D models. With the introduction of CAE, engineers and designers can now incorporate a broader range of material compositions into their 3D models, resulting in more accurate and realistic representations of the final product, (Liu, Duke et al. 2015). Applying materials to 3D models opened the door to new design phases such as a) finite element analysis (FEA), which is a computerised method to predict how a product reacts to different physical forces such as vibration, heat, fluid flow, and other environmental conditions, and b) computer-aided manufacturing (CAM) that uses this model to generate instructions for the machine tool, such as which tools to use, which paths to follow, and how fast to move. This helps to automate the manufacturing process, reduce errors, and increase efficiency. CAM is used in various industries, including aerospace, automotive, and medical device manufacturing, (Chang 2016).

3.3 3D Models used in manufacturing processes

Manufacturing processes are the steps and methods used to transform raw materials into finished products. These processes can vary greatly depending on the product type, the materials used, and the resources available. Some standard manufacturing processes include casting, forging, machining, welding, and assembly. Each process involves different tools, machines, and techniques to shape and form the raw materials into the desired product. Quality control measures are taken throughout the manufacturing process to ensure that the final product meets the necessary standards and specifications. Manufacturers can increase efficiency, reduce waste, and improve productivity by optimising these processes, (Swift, Booker 2013).

The manufacturing industry has witnessed a significant transformation with the introduction of CNC (computer numeric control) programming, driven by the need for enhanced efficiency and precision in production, surpassing the capabilities of traditional machine tools. Nonetheless, it is worth noting that a part program only captures a fraction of the data accessible in a CAD/CAM setting, which contains enough information for the numeric control

(NC) cutter-path programming, (Xu, X. W., He 2004). As per (Russo, Zhang et al. 2024) definition, machine tools are devices that facilitate the shaping or moulding of rigid materials, mainly metal, through processes that involve milling, drilling, boring, cutting, and grinding. A machine tool generally comprises fixtures that stabilise the workpiece, a tool that carries out the specified manufacturing operation, and a system that directs the tool along a predetermined path. Other mechanisms may also be incorporated to perform product manipulation and assembly.

Rapid prototyping (RP) is another manufacturing process involving advanced technologies to fabricate precise components directly from CAD models with minimal human intervention. RP technologies enable designers to create physical models of their designs in hours, allowing them to iterate more quickly and precisely. Unlike traditional manufacturing methods, RP technologies offer greater design flexibility, allowing designers to rapidly produce complex geometries and functional prototypes. RP technologies have revolutionised how products are designed and developed, making it easier for designers to validate their concepts and bring them to market faster, (Pham, Gault 1998). But (Gibson, Rosen et al. 2015) says that users of RP technology have realised that the term needs to be updated and that the latest applications of the technology need to be described effectively. With advancements in the production quality of these machines, the link to the final product has become much closer. Many parts are now produced directly on these machines, making the term "prototypes" inaccurate. Additionally, the term "rapid prototyping" fails to acknowledge the fundamental principle of these technologies: additive manufacturing. A technical committee formed within ASTM International has agreed that new terminology is necessary to address these issues. While this is still being debated, ASTM consensus standards now recognize the term "additive manufacturing" for these recently adopted technologies.

4. PRODUCT LIFECYCLE MANAGEMENT (PLM)

4.1 PLM Definition

Any product's lifecycle can be broken down into a series of distinct phases, including the conceptualization of a business idea, requirements analysis, development, production, operation, maintenance, and eventual disposal. However, it is worth noting that the definition of PLM (product lifecycle management) can vary depending on the particular research field being considered. While some define PLM as a strategic business approach (as per CIMdata), others view it as an information-driven approach (as per Grieves and the PLM Development Consortium). Still, others, such as Siemens and AMR, approach PLM from a computer science perspective, defining it as either an information management system or a suite of software applications, (Morshedzadeh, Ng et al. 2021a). Product Lifecycle Management (PLM) is a strategic business approach that supports the collaborative creation, management, dissemination, and use of product definition information within and across the extended enterprise, integrating people, processes, technologies (Corallo, Marra et al. 2019), its partners and suppliers, (Cantamessa, Montagna et al. 2012).

4.2 PLM in Manufacturing Industry

In the fourth industrial revolution, Industry 4.0, digital factories are constructed using engineering techniques such as virtual modelling and simulation. Effective management of manufacturing data and information is crucial in these endeavours. Product lifecycle management (PLM) is indispensable for virtual development due to its role in manufacturing data in Industry 4.0. Therefore, updated manufacturing data and information are pivotal in the creation of digital factories, as well as in conducting virtual and cloud engineering activities. PLM systems are instrumental in managing this data and information, (Morshedzadeh, Ng et al. 2021b).

Developing modular product designs using visual product models poses significant challenges, particularly in dynamically managing large amounts of information. These challenges arise from integrating development across multiple departments, which could involve thousands of employees. One of the difficulties is identifying and managing modules and interfaces, given that product data is scattered across various CAD systems and architecture descriptions. Designers often struggle to locate and re-use existing modules, and monitoring design progress during project development can be challenging due to the distributed nature of the process. Additionally, managing interfaces, including designing and controlling them, is complex, (Bruun, Mortensen et al. 2015).

5. Case Study

This chapter will present two case studies which involve manufacturing companies still relying on 2D drawings in their design process. One of the objectives is to gain a comprehensive understanding of the pros and cons of this approach, as well as to investigate why some companies may choose to stick with the traditional method instead of exploring newer solutions. Ultimately, it hopes to provide valuable insights enabling manufacturing companies to make informed decisions regarding their design processes.

5.1 Case Study 1

A case study was carried out on an aircraft interior manufacturer in the picturesque south coast of Dorset, England. The study was conducted from March 2019 to February 2020. This manufacturing company has notable expertise in aircraft cabin design and development. They specialise in producing top-quality galleys, business and first-class seats, and all the inflight services needed to ensure an enjoyable experience for passengers. This organisation boasted over three decades of expertise in its industry and had a workforce of 647 skilled professionals by 2020.

This primary data was collected when designing two front-row monuments to be fitted on an Airbus aircraft (A321) for a US airline (see figures 4 & 5). This project was a collaborative effort that spanned approximately nine months and involved the work of five designers. The primary manufacturing techniques employed included composite materials, computer numerical control (CNC), vacuum forming, and sheet metal components. However, it is essential to note that the data compilation does not account for any electrical or piping installations required.

The data presented below were meticulously collected by each of the five engineers in the design team allocated for this program. They diligently filled out an Excel sheet file in a shared location, listing the most used activities during a development project with the mentioned characteristics, adhering to the standard practice in the business.

The data to be collected was divided into two main groups. The first group focused on recording all the hours invested in using 3D CAD. This would be used for the design of detailed parts, the creation of assemblies, and the integration of these in the DMU (Digital Mock-Up). A digital mockup or a digital prototype is a computer-generated model of a product or design that helps designers and engineers visually represent a physical object and simulate how it looks and functions in real life. It is an effective way to test different features and functionalities of a product before it is manufactured, which can help reduce costs and improve the overall quality of the final product, (Friel, Marzano et al. 2015).

It also included other specific design tasks focused on creating 3D models for the physical mock-up required in the detailed design review (DDR).

The second group was focused on everything related to 2D CAD, ensuring a comprehensive data collection. This included the drawings for the detailed parts and assemblies, in addition to the drawings of the composite material structure.

Figures 4 and 5 have been prepared to present a detailed breakdown of the time and effort invested in creating 3D designs and 2D drawings for this project. These graphs provide a comprehensive overview of the time spent on each task and shed light on the percentage of resources allocated to each activity. Additionally, these charts offer valuable insights into the time spent revising 3D models and 2D drawings that did not meet the approval criteria during the release process.

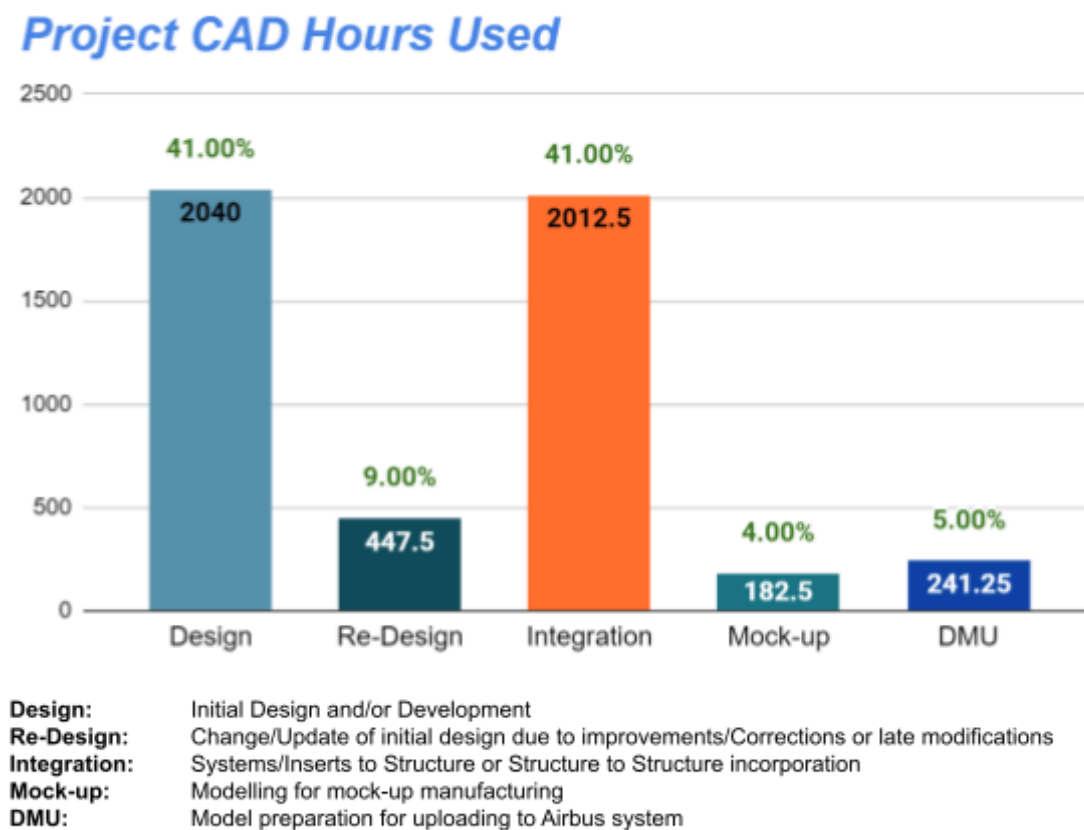


Figure 4. Case 1, project hours used in 3D CAD environment

This chart indicates that an equal percentage of hours (41%) was devoted to designing individual parts and assemblies. Designing individual parts encompasses modelling parts with various manufacturing methods like machining, sheet metal, vacuum form, and composite materials. Flat and moulded sandwich panels were utilised for the composite materials since they are simple designs. The integration part consists of different types of assemblies, ranging from a machined block with inserts or a bracket with anchor nuts to an

assembly comprising approximately 900 pieces. Due to the assembly's complexity, many hours were invested in integrating the final products.

Re-design comprises 9%, which refers to the modifications required when the release process results in rejected designs that do not meet the client's requirements, the manufacturing process, or the work methodology when designing according to company standards. The two lowest percentages represent the time spent on the digital mock-up (DMU), which entails assembling the final product with the aircraft interfaces. The physical mock-up (prototype design) is employed to showcase, evaluate, agree on, and modify the product's evolution before releasing it for production.

Project Drawing Hours Used

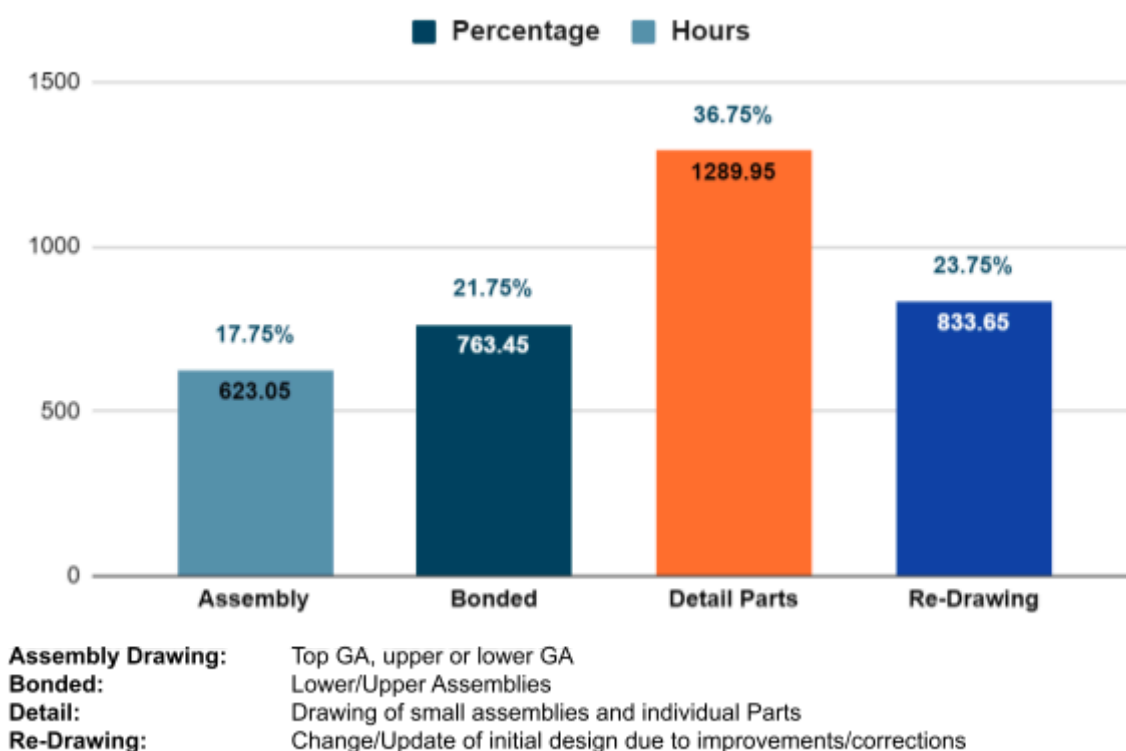


Figure 5. Case 1, project hours used in 2D CAD environment

A notable observation from this figure 5 is the significant emphasis placed on drawings within this manufacturing company. Most of the working hours were devoted to the development of intricate part drawings, which was the most challenging task. The second most difficult task involved modifying the drawings that were rejected during the release process due to non-compliance with the company's established standards. The organisation maintains a clear distinction between all-encompassing bond assemblies and top-level assemblies, which contain lengthy items in the Bill of Materials (BOM) to facilitate smooth integration with the aircraft supplier and the airline. The Bill of Materials (BOM) is a crucial document that helps manufacturers specify the exact components and materials required to

build a product. It provides a structured representation of the product's configuration, including the relationships between the final products, their parts, and materials. This document also outlines the quantities of subordinative parts and materials required in each assembly, helping manufacturers streamline their production processes. BOM provides a structure representation to specify the configuration to build a product, including the relationship between the final products, parts, or materials and the quantities of the subordinative parts and materials required in each assembly, (He, Ni et al. 2014).

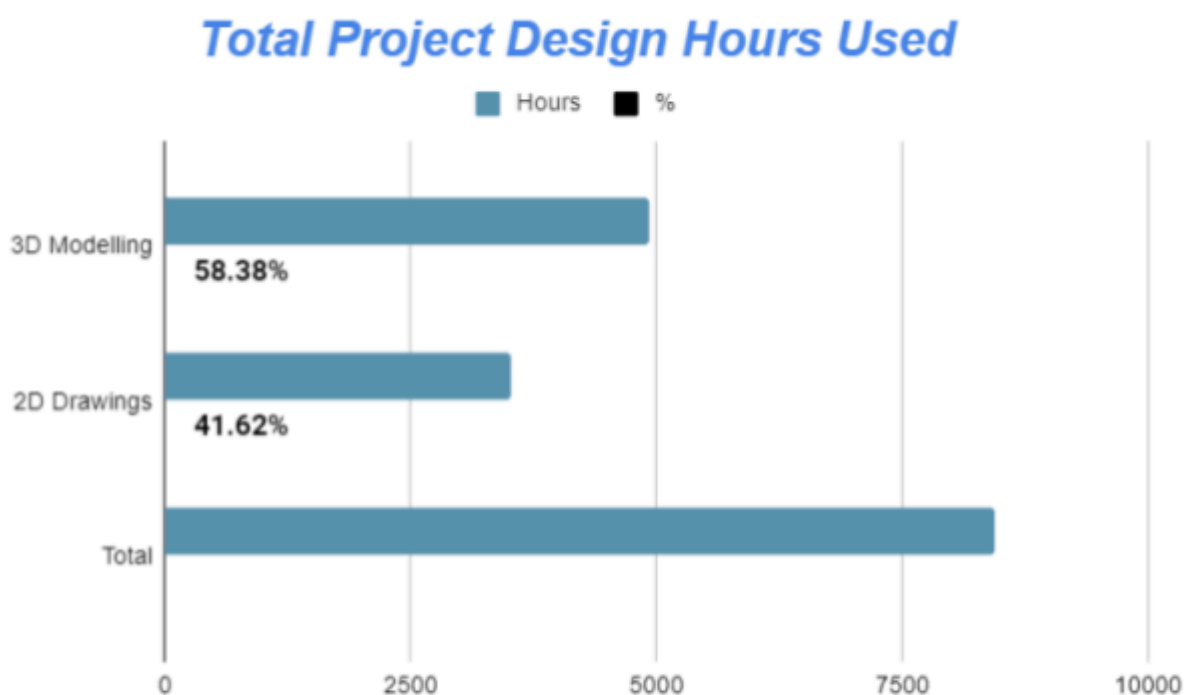


Figure 6. Case 1, total project hours used in 3D & 2D CAD environment

The data presented in Figure 6 provides valuable insight into the allocation of time and resources for the design project. The figures reveal that almost 60% of the 8433.75 hours dedicated to the project were spent on 3D work, with the remaining 40% allocated to 2D work. Notably, the high percentage of hours dedicated to computer-aided design (CAD) drawings indicates the company's significant emphasis on this task. This emphasis on CAD is further exemplified in Figure 5, which shows that nearly a quarter of the time spent on CAD work was utilised to modify drawings rejected from the release process. Such details highlight the intricate and meticulous process involved in the design project and underscore the need for careful planning and execution.

5.2 Case Study 2

The manufacturing industry plays a vital role in South Wales' economy, (, A manufacturing future for Wales: our journey to Wales 4.02023). This case study will examine a leading manufacturing company based in the region. Renowned for its exceptional business and first-class seats, this world-class company excels in designing, producing, assembling, and certifying top-quality products. With decades of experience and hundreds of employees across various departments, this company has become a key player in the manufacturing industry. However, intense competition remains a significant challenge that requires the company to innovate and enhance its products to stay ahead continuously.

The industrial and design engineering teams face the challenge of meeting customers' growing need for personalised products. Achieving this level of customization requires constant innovation and optimization of the manufacturing processes (Rungtusanatham, Salvador 2008), to ensure that the final product is not only exclusive but also meets each customer's unique requirements. This involves considering various factors, including material selection, manufacturing techniques and design principles. The teams must also work collaboratively to identify any potential bottlenecks in the production process and develop practical solutions to ensure that the customer's expectations are met in terms of quality, cost, and delivery, (Davenport, Short 1990). Ultimately, the manufacturing process's success lies in the teams' ability to balance the need for personalization with the need for efficiency and scalability.

In this case, one of the current first-class seating programs running by the company has been taken in its preliminary design freezing phase, which gives way to the critical design review (CDR), where the design will be reviewed and approved by the client and the integrators of the final product. A CDR is a review that assesses whether the detailed system design meets the performance and engineering requirements specified in the development specifications, (*The Critical Design Review Process for Major Defense Acquisition Programs*. 1992).

The technical drawings are valuable for this company's product design and production. They provide a detailed blueprint of the product's specifications and requirements, a reference for the entire production process. Pertinent data has been collected for six months to analyse the current workflow (WF) process and assess the impact of the drawings on it. A workflow, often called a business process, is vital to organisational management. It is a systematic approach to managing work processes in an organisation. The term workflow is also used to

describe the control dimension of a business. Its primary purpose is to ensure that the proper work is delivered to the right resource at the right time.

The workflow process is a critical aspect of organisational productivity and efficiency. It involves the identification of work processes, the allocation of resources, and the establishment of a timeline. An effective workflow process enables organisations to optimise their resources, reduce costs, and improve the quality of their products or services, (Reijers 2003). The insights gained from this analysis will help to provide a closer overview to compare the current system with new processes.

As previously indicated, the multinational program in question involves design engineers from various countries, such as India, the US, Mexico, and the UK, who participate in finalising designs and releasing drawings to the CDR. The team's data collection remained unaffected despite working from different locations because they were all connected to the same PLM system. This system captures all the information used in the project, from the receipt of styling data by the design department, whether produced internally or by an external office selected by the client, to the product's continued service. The PLM system's advantage is that it enabled the weekly collection of data on the drawing release process, which was more detailed than in the earlier case study. The collected data on the workflow process of the drawings analysed here provides a detailed view of the flow of the drawings over time. However, the most significant aspect is the efficacy and productivity of the company's standardised process concerning technical drawings as a unique tool to produce the detailed parts that will be utilised later in the CDR.

In the graphical representation presented in Figure 7, the count of drawings initiated during the six-month period of the release process is showcased, along with the number of rejections made during the same timeframe. As part of this process, the initial stage involved an evaluation conducted by a design checker, followed by a review of the design's manufacturing and assembly aspects by other teams in the subsequent stage.

DWG Workflow Rejections

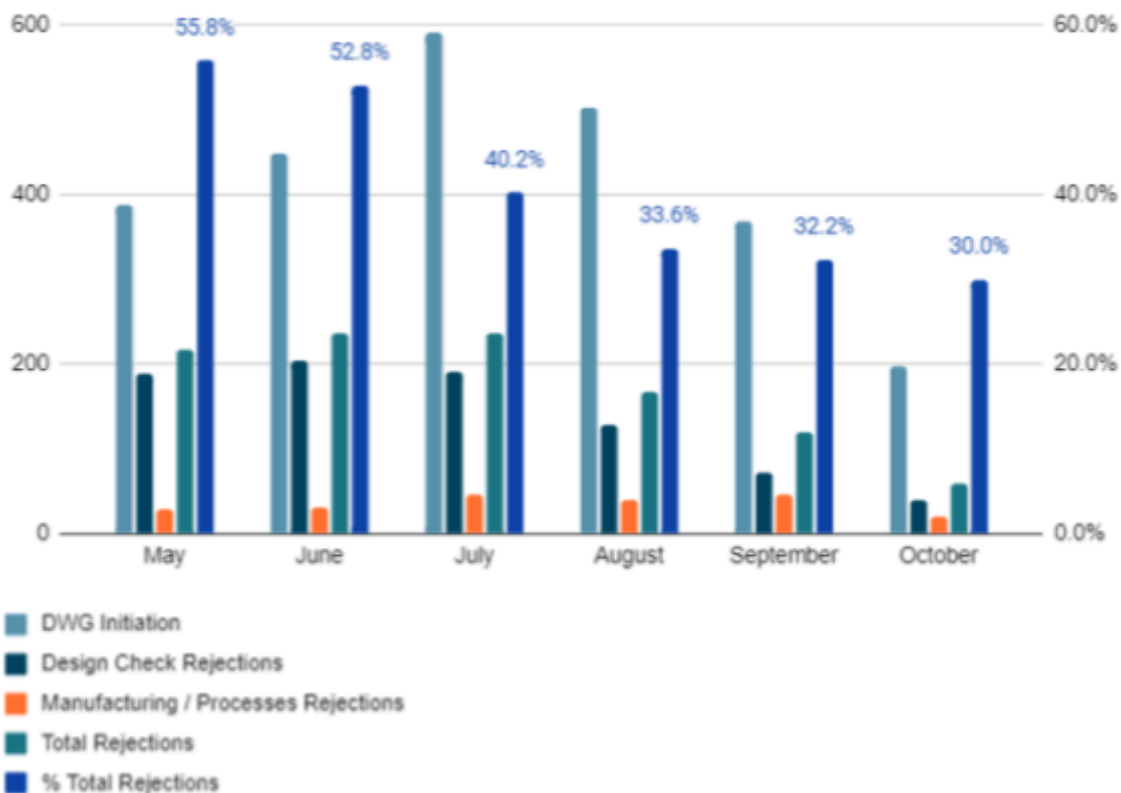


Figure 7. Case 2, the number and percentage of DWG workflows created and rejected in six months.

This chart displays the number of drawings commenced during launch, the number of rejections issued by the design checker in stage two, and those from the manufacturing department for individual parts and assemblies. The last two sections of the chart exhibit the overall quantity of rejections and their corresponding percentages. Over six months, the chart exhibits a distinct pattern in the initiation of drawing launch procedures.

Upon studying the graph closely, it becomes evident that there was a considerable increase in the number of initiations from the first month to the third month, followed by a decrease in the final month. It is important to note that this fluctuation in the number of initiations is primarily subject to the volume of designs available for freezing at any given time. This volume is contingent upon several factors, including but not limited to the designers' priorities, the intricacy of the manufacturing processes, and any potential delays that may be caused during the production phase.

During the first two months, more than half of the processes were rejected, but there was a gradual decline in the rejection rate over time, reaching 30% in the last month.

The design checkers, however, maintained a high rejection rate until the third month, after which there was a marked downward trend, ultimately reaching around 5% in the final

month. The manufacturing and assembly teams also saw a consistent trend in their second check, with a significant drop in numbers in the final month.

Figure 8 and Table 1 detail the reasons and number of rejections, categorised by the stipulated guidelines. These visual aids offer a comprehensive overview of the reasons for the rejections, enabling a thorough analysis of the underlying reasons.

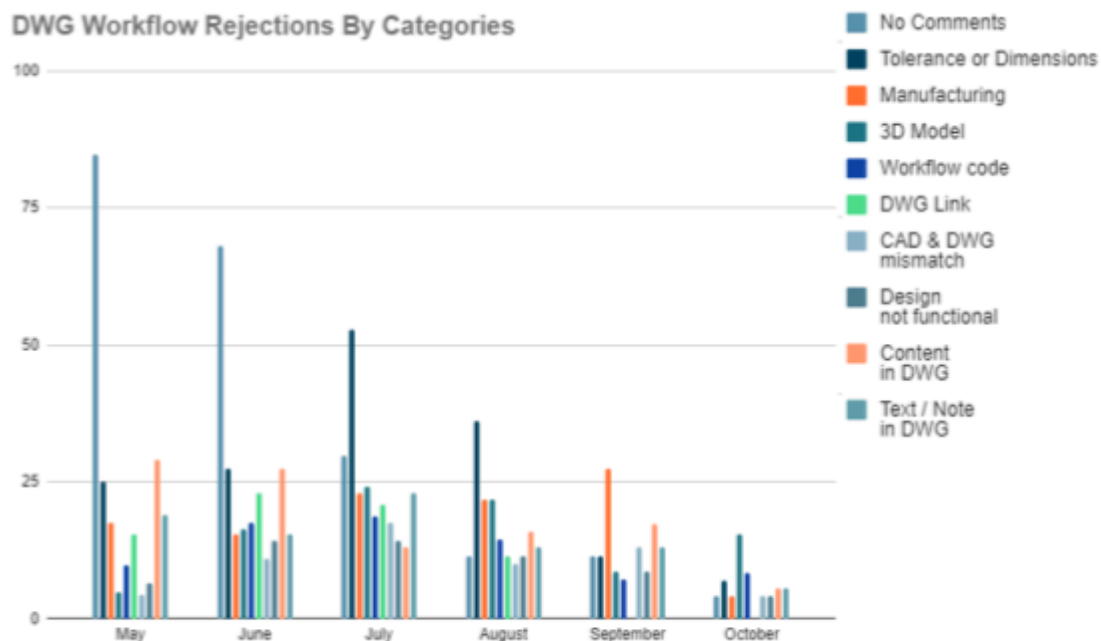


Figure 8. Quantities of the standard categories used to reject drawings in the WF process.

Rejections used in the workflow process														
	DWGS Initiated	No Comments	Tolerance or Dimensions	Manufacturing	3D Model	Workflow code	DWG Link	CAD & DWG mismatch	Design not functional	Content in DWG	Text / Note in DWG	Total DWGS Rejected	% Total Rejections	Total DWGS Approved
May	388	85	25	18	5	10	15	4	7	29	19	217	55.8%	171
June	448	68	28	15	17	18	23	11	14	28	15	237	52.8%	212
July	591	30	53	23	24	19	21	18	14	13	23	238	40.2%	353
August	502	12	36	22	22	15	12	10	12	16	13	168	33.6%	334
Sept	369	12	12	28	9	7	0	13	9	17	13	119	32.2%	250
October	198	4	7	4	15	8	0	4	4	6	6	59	30.0%	139

Table 1. The most common standard categories used to reject drawings in the WF process.

After analysing the data, it is clear that most rejections in the initial two months resulted from incorrect procedures, with no accompanying explanation for why the drawing was rejected. Fortunately, this occurrence has substantially reduced from 85 to just four rejections last month. Nonetheless, this error has led to an unacceptably high number of rejections that could have been prevented if proper adherence to the company's standard processes and the inclusion of an explanation for the rejection had been observed.

The company's procedures revealed that the most frequent kinds of rejections were related to errors in tolerances or dimensions in the drawings. In July, there were a considerable number of 53 rejections, but this number gradually decreased until it reached only seven rejected drawings due to the same errors in October. The rejections mentioned by manufacturing refer to an amount divided between rejections made due to errors in the manufacturing process (machining, sheet metal, vacuum form, additive manufacturing) and errors in sub-assemblies due to difficulties in the execution or the incorrect selection of processes such as riveting, bonding incompatible elements and inserts.

Administrative errors can occur when dealing with workflow code and DWG links. The workflow code is a distinct code that must be added to the PLM tool in order to distinguish between projects within a company. This code assists in extracting information from the system for further data analysis. Similarly, DWG links are utilised to attach 2D and 3D models when initiating the workflow process for drawing release. Errors can arise if different revisions are handled among the models. It is worth noting that mistakes in drawing links were eliminated in the last two months, showcasing an improvement and good practice to avoid rejections for this reason.

Another number of rejections are attributed to the contents, texts and notes used in the DWGS. These errors, as their names indicate, refer to annotations, flag notes, reference texts and in the notes used to designate the processes to be used that are part of the company's standard notes. While various analyses could be drawn from this data, only the most relevant to the research objectives have been mentioned.

This case study delves into the reasons behind the rejections encountered during the workflow process. The study presents a conclusive chart, figure 9, which demonstrates that an overwhelming 70% of the rejections were caused by errors related to the drawing process. The remaining 30% of rejections were attributed to various factors, including inaccurate design solutions, modifications made to the 3D model, and an insufficient understanding of the various manufacturing processes involved. The study's findings highlight the importance of paying close attention to every detail related to the drawings and emphasise the urgent need for a comprehensive understanding of the various manufacturing processes to avoid or minimise the number of rejections as much as possible.

Main Workflow Rejections Reasons

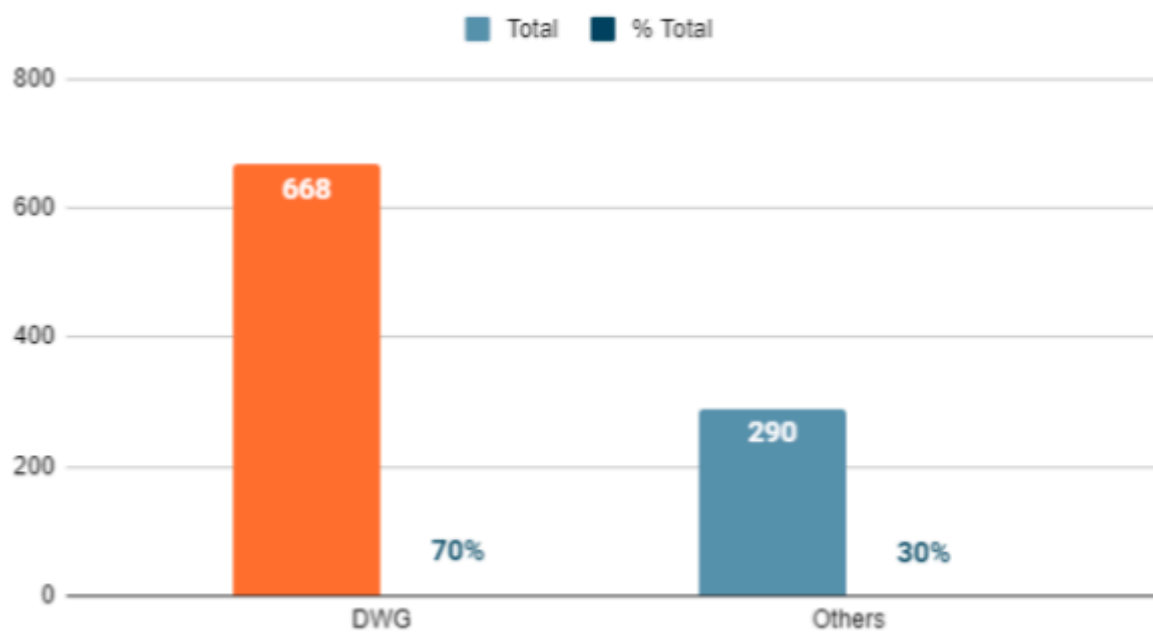


Figure 9. Workflow rejections divided by errors caused by drawings and other reasons.

DISCUSSION

6 Discussion case studies

6.1 Discussion Case Study 1

During the initial data collection phase, the author observed that the work patterns and systems employed across three projects, including the current one, were strikingly similar. This provided an opportunity for a comprehensive analysis of the high volume of rejected drawings and the need for subsequent modifications. Also, investigations revealed that the company did not have a well-established checklist for reviewing designs and drawings before their release, leaving the drawing checkers to rely solely on their knowledge and experience. This practice resulted in a high incidence of discrepancies, often dependent on the individual assigned to check the drawings. This was particularly problematic due to the company's employment of both permanent staff and contractors.

The automotive manufacturer's practical management of synchronisation in their processes can be attributed to their extensive use of engineering checklists. These checklists mitigate the risk of foreseeable errors or those that have happened in the past by encoding them into the checklists, effectively preventing their recurrence, (Ćatić, Malmqvist 2013). A checklist that is both comprehensive and easy to use would greatly assist designers and support checkers in validating their designs. It also enables feedback to be provided to the designers and captures details that could lead to rework cycles, thus facilitating the identification of areas for improvement.

Accessing design guidelines and manufacturing processes was problematic due to the need for a centralised organisation. Depending on the person consulted, different locations were suggested, resulting in using outdated revisions and subsequent rejection of designs and drawings during the release process to not be up to date. The collaboration and coordination between the various departments involved in the release process, including stress, certification, flame, and purchasing, could have been much better. The company still needs to rely on a manual process where designers must physically print out the drawings and carry them to these departments for signatures, which hinders the progress of the entire process. It is expected to see piles of drawings on desks awaiting release, and locating the ones requiring immediate attention can take time and effort. The absence of automation in these processes exacerbates the situation, making it even more challenging to gather actionable information that can be used to enhance the design department's operations.

It is important to note that much paper is utilised and discarded during the design process.

This is because designers often need to print several copies of their drawings before selecting the final version for submission. Any rejected drafts are then subsequently discarded. As a result, the design process consumes a significant amount of paper, and the company needs to consider adopting eco-friendly practices to reduce waste and minimise its ecological footprint.

As it witnesses an increasing number of design companies striving towards developing sustainable products (Maxwell, van der Vorst 2003), it is equally crucial that they evaluate ways to enhance their operations to curtail waste, mitigate air, land, and water pollution, and minimise health hazards to all living beings. This entails conserving energy and materials, eliminating toxic substances, reducing waste generated during the design of products and production, and setting comprehensive sustainability goals encompassing environmental, economic, and social aspects, (Buzuku, Kässi 2019).

6.2 Discussion Case Study 2

During this primary data collection, it was revealed that many drawings were rejected, including those without comments, in the first few months. The author found that this could be attributed to four main factors. The program required additional staff from the beginning and needed more personnel to be hired. Secondly, the timeline for new product development to critical design review was inadequate due to incomplete product design specifications (PDS) and frequent modifications. A Product Design Specification (PDS) encompasses design inputs, constraints, goals, product performance, environment, quality, reliability, security, lifecycle, and other pertinent elements. It is a comprehensive document outlining the design requirements and specifications for a product, (Zhang, Han et al. 2016). Additionally, many designs required physical testing, which could not be completed within a reasonable time frame due to staffing shortages in the industrialization department. Thirdly, introducing inexperienced personnel to the team or moving staff between programs without knowledge of the new product caused disruptions. Finally, the current PLM (Product Lifecycle Management) system, implemented with limited success, relied on manual updates for every revision, which proved time-consuming and ineffective. In summary, the high number of rejected drawings, including those without comments in the first few months, was due to the program requiring additional personnel, an inadequate timeline for new product development, staffing shortages in the industrialization department, disruptions caused by inexperienced personnel, and an ineffective PLM system that relied on manual updates every time revisions are modified before being pushed into the WF.

Upon analysing the errors illustrated in Figure 8 and Table 1 about tolerances or dimensions,

the author observed that some designers needed to improve their knowledge or experience regarding the manufacturing process they are working with. A few years back, the company implemented a technique involving drawings with smaller quantities of dimensions to hasten their creation and review during the release process. This approach relies mainly on the standardised tolerances provided within the drawing box, reducing the critical dimensions that must be scrutinised. Consequently, the author made the design department's management aware that the ongoing design process presents a significant risk to the products being produced. This risk is mainly due to some designers and checkers who require assistance comprehending the critical dimensions involved in the process. The lack of understanding leads to incorrect sizing of dimensions and improper usage of tolerances, which endangers the quality of the products.

Furthermore, the author also revealed that the current tolerances used as industry standards were incompatible with those employed by the composite panel supplier. This lack of compatibility resulted in notable challenges during the assembly of the products, ultimately leading to substandard safety measures and an overall compromise in product quality.

6.3 Link to next section

As observed in the literature review, the realm of drawings and designs has undergone a substantial transformation, spanning from stone and manual sketches to cutting-edge technical drawings for product manufacturing and CAD stations for 2D and 3D designs. It is essential to recognize that this change has occurred over an extended period; nevertheless, difficulties persist in the release procedures with technical drawings, as evidenced by the two cases examined. Novel technologies have emerged to enhance operational efficiency and mitigate risks associated with traditional manufacturing processes, including Model-Based Definition (MBD), Additive Manufacturing (AM), and Generative Design (GD), which will be presented in the following sections. These technologies aim to reduce or eliminate dependency on technical drawings, advancing manufacturing processes to a more streamlined, automated, and intelligent stage.

7 INDUSTRY 4.0

7.1 Industry 4.0 as steady improvement

As for its three proceeding Industrial Revolutions, the fourth industrial revolution (Industry 4.0) represents an unprecedented fusion between and across digital, physical and biological technologies, and a resulting anticipated transformation in how products are made and used, (Maynard 2015). Industry 4.0 is all about continuous improvement. With the help of advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML), companies can collect and analyse vast amounts of data in real time. This data can then be used to identify areas for improvement and optimise processes for maximum efficiency. By embracing the principles of Industry 4.0 and investing in the right technology, companies can stay ahead of the competition and achieve long-term success, (Peças, Encarnação et al. 2021).

Implementing Continuous Improvement (CI) initiatives is crucial for manufacturing organisations to generate strategic benefits and overcome international competition. In today's highly competitive marketplace, CI has become an essential strategy for businesses to stay ahead of the curve. An effective CI implementation program can help organisations address their improvement-related problems and ensure their equipment performs optimally, (Singh, Singh 2015), and this is why CI is a key part of Industry 4.0, as it enables companies to identify opportunities for optimization and leverage the power of technology to drive sustainable growth, (Arredondo-Méndez, Para-González et al. 2021).

An intelligent production system can seamlessly integrate various Industry 4.0 concepts to create an efficient manufacturing process. This system employs web technologies, CAD/CAE 3D parametric tools for design, additive manufacturing (AM), and robotic factories for product assembly with minimal human intervention, (Mattos Nascimento, Alencastro et al. 2019). The role of smart machines and smart factories equipped with the Cyber-Physical System (CPS) in the manufacturing industry cannot be overstated. This cutting-edge system facilitates integrating, managing, and synchronising activities and processes between digital and physical spaces, enabling efficient data retrieval and analysis. Manufacturers can optimise their operations with the CPS by leveraging real-time data and insights to make informed decisions, streamline workflows, and improve overall efficiency. It is a game-changing technology that is revolutionising the manufacturing industry, and it is crucial to acknowledge its significance, (Pereira, Romero 2017).

8. Model Base Definition (MBD)

8.1 MBD

MBD, or model-based definition, is a modern methodology that utilises 3D models as comprehensive sources of information for various engineering and business processes. These processes include design, production, distribution, technical documentation, services, and overall product lifecycle management. By incorporating 3D models, MBD offers a new and efficient way to manage and streamline these processes, (Geng, Tian et al. 2014). In modern design, it is not uncommon to come across multiple interpretations of the same design, which can result in confusion and even conflicts. For example, a 3D model and a drawing of the same component may be released simultaneously, resulting in duplicate design definitions. However, implementing a Model-Based Definition (MBD) dataset can establish a single-source definition of the design, effectively eliminating any potential conflicts between CAD and paper drawings. By utilising an MBD dataset, there is no requirement for multiple definitions of the same design, as it provides a comprehensive and precise representation of the design that can be effortlessly shared and accessed by all involved stakeholders throughout the project, (Goher, Shehab et al. 2021). (Zhou, Fan 2010) further says the MBD system has two main elements: the MBD assembly and component models. The MBD component model consists of a design model, which serves as a comprehensive digital definition of the product's manufacturing information and the geometric representation of the product's design using simple geometric elements and annotation and attribute data expressed symbolically. On the other hand, the MBD assembly model comprises a series of MBD component models, including annotation and attribute data that are also expressed symbolically. The component design model also contains built-in information such as raw material specification, analytical data, and test demand. Annotation data, on the other hand, contains manufacturing constraint information, including product size and tolerance, fabrication technology, and accuracy requirements, among others.

8.2 MBD in manufacturing

There is a growing trend towards MBD technology replacing traditional 2D drawing throughout the product life cycle. 3D models offer more comprehensive and precise machining, which can be utilised for intelligent modelling, estimation, and optimization when combined with machining annotation. Additionally, 3D software enables designers to

annotate GD/T manufacturing information directly onto the model, providing an efficient and effective tool for the job, (Wan, Mo et al. 2014).

In his research, (Bai, Dallasega et al. 2020) has introduced a system that extracts inspection information from the MBD model and generates an inspection plan closely associated with it. By establishing a connection between inspection data and geometry characteristics in the MBD environment, the inspection system can generate CMM measurement programs interactively. This three-dimensional inspection plan can be quickly published using MBD technology and cloud manufacturing platforms. Furthermore, it can be accessed by both cloud service demanders and manufacturing service providers through a lightweight model. Another research has highlighted the significance of Model-Based Definition (MBD) technology in providing essential process information to facilitate the assembly site application. Using three-dimensional assembly instructions enables conveying process design outcomes to the workshop assembly site, leading to an improved working environment, better product quality, and increased production efficiency. In the spacecraft assembly domain, digital assembly technology is proving to be a game-changer. It is expected to play a crucial role in the growth and success of the industry, (Song, Lu et al. 2018).

Engineers will save time because they no longer need to select between different sections and views as they did when working with 2D technical drawings. With 3D models, all the necessary information is provided within the model, eliminating the need for engineers to worry about placing views on a limited paper format. However, engineers can still choose which views they want to use for their dimensions. This flexibility is similar to drawing each view on a separate sheet of paper, allowing engineers to work without space limitations. Additionally, the use of Model-Based Manufacturing techniques in conjunction with CAD-CAM transformation can automatically generate a manufacturing strategy, which was a task that production engineers previously did, (Križaj, Vukašinović 2019).

8.3 Implementations Considerations

When supporting MBD, the CAD tool must ensure that it aligns with the requirements of the local process. Design engineers can derive immense benefits from CAD libraries, which save time and promote consistency. These libraries consist of standard hardware components such as washers, bolts, connectors, and more, eliminating duplication of effort and guaranteeing that these items are placed in the correct orientation, (Gregory 2012). Product Lifecycle Management (PLM) integrates Computer-Aided Design (CAD), digital manufacturing, and simulation with the Enterprise Resource Planning (ERP) system,

enabling a seamless integration of design, manufacturing, and business operations. This optimization of product development and delivery processes makes PLM an essential tool for managing the product life cycle, (Alemanni, Destefanis et al. 2011).

For those who currently work with 2D drawings, training is essential. CAD users can take courses to learn how to use design tools for MBD and annotate a 3D model to reflect all the product manufacturing information (PMI), depending on the CAD package. This training may also include transferring data to neutral file formats for downstream users. It is recommended that CAD users receive training first, as they will serve as the primary resource for training other departments, (Gerbig 2017).

It is imperative to have a well-documented methodology for designing and managing a project. Creating consistently well-built and sturdy designs makes them easier to share and integrate into more complex systems to guarantee that the CAD models produced for manufacturing are what is needed. It is crucial to establish configuration management processes from the start of the project until its completion, (Gregory 2012).

9. Additive Manufacturing (AM)

9.1 Additive Manufacturing definition

The term "additive manufacturing" refers to manufacturing techniques that produce objects layer by layer, enabling the creation of three-dimensional products on demand. This technology is often referred to as 3D printing, and it has revolutionised the manufacturing industry by providing a more efficient and flexible means of production, (Ford, Despeisse 2016). Among the most widely used additive manufacturing (AM) technologies today are Fused Deposition Modelling (FDM), which employs a thermoplastic filament to produce objects; Stereolithography (SLA), which involves curing a liquid photopolymer with a laser to create objects; Selective Laser Melting (SLM) and Selective Laser Sintering (SLS), which use lasers to melt or sinter metal or plastic powders to create objects; and Digital Light Processing (DLP), which employs a projector to cure a liquid photopolymer to create objects. Nevertheless, numerous other AM processes exist, such as PolyJet, which employs multiple print heads to create objects with various materials, and Electron Beam Melting (EBM), which employs an electron beam to melt metal powders to create objects, (Petrovic, Haro et al. 2010).

The benefits of additive manufacturing are plentiful when compared to traditional manufacturing methods. Its ability to produce intricate designs expeditiously, the lack of need

for specialised tools, and the capacity to create bespoke items in limited quantities are just a few, (Sasson, Johnson 2016). Furthermore, additive manufacturing can significantly lower product development expenses and timeframes by facilitating swift prototyping and refinement, (Ballardini, Iñigo Flores Ituarte et al. 2018).

Additive manufacturing is set to revolutionise several industries, such as aerospace, automotive, medical, and consumer products. This innovative technology enables the production of personalised products with minimal waste, paving the way for a new manufacturing and product design era. Its widespread adoption promises to bring significant changes to the industry landscape, (Wong, Hernandez 2012).

9.2 Process interaction with 2D drawings

Technical drawings have a particular characteristic that differentiates them from other drawings called GD&T. These tolerances are guided by the ASME Y14.5 (ASME Y14. 5 2009) standard. The GD&T system serves as a valuable means of communication between engineers and manufacturers, enabling them to convey critical information regarding product manufacturing. Engineers must indicate the necessary tolerances when requesting quotes, while manufacturers must inform potential clients of their established limits, (Bradford 2018).

It is important to note that one of the challenges this system faces is its ability to integrate with advanced technologies like AM and GD. These technologies offer a vast array of design solutions without the same limitations imposed by traditional manufacturing processes, (Ameta, Witherell et al. 2015). Innovative approaches are required to effectively communicate Geometric Dimensioning and Tolerancing (GD&T) in the context of Additive Manufacturing (AM). These approaches should feature Product Manufacturing Information (PMI) and representation techniques. To support AM products, specific steps are vital, including tolerance of complex surfaces, communication of tolerances related to diverse materials and internal geometries, conveying dimensioning and tolerancing requirements across various product lifecycle stages, and enabling machine-readable dimensioning and tolerancing from design to manufacture to conformance and verification, (Witherell, Herron et al. 2016).

9.3 Generative Design

The generative design process involves utilising both an expert and an optimization system to generate and evaluate potential solutions. This approach can automate some or all of the traditionally manual design process using algorithmic tools. As a result, designers can produce higher-performing components in a shorter time, with improved certification capabilities, and at lower costs. By leveraging generative design, businesses and academic institutions can achieve better outcomes, optimise resources, and streamline the design cycle, (Watson, Leary et al. 2022).

Engineers seeking to optimise the geometry of 3D models can benefit from utilising geometric dimensioning (GD) tools. These innovative tools provide valuable support during the conceptual and modelling stages by allowing designers to focus on function over form. Unlike traditional design methods that use CAD systems to generate detailed geometry based on a designer's input, GD tools delegate optimization to generate design alternatives. This approach empowers designers to use CAD systems solely for defining functional surfaces. In the final stage, CAM systems ensure correct manufacturability, a crucial element in the process. The adoption of GD tools represents a significant shift from traditional design methods that rely solely on CAD systems to generate detailed geometry. By utilising GD tools, designers can create more effective and efficient designs that meet the necessary specifications and requirements, (Barbieri, Muzzupappa 2022).

One cutting-edge 3D printing technology is the GD and AM method, which constructs objects layer by layer. This process begins with a digital 3D model divided into sections, serving as a blueprint for the machine to produce the physical object. This technology can use a diverse range of materials, such as plastic, metal, ceramic, and even biological materials, (D'angeli 2023).

CLOSING

10. Conclusion & recommendations

According to research, drawing is essential to transcribing and representing individual ideas and imaginations and defining and achieving the right product depending on the manufacturing process. It is also used in conveying these ideas during conversations, allowing for creating art, meeting needs, and understanding and solving problems by facilitating a dialogue between a designer and their concept (Gherghina, Tutunea et al. 2017). However, while drawing is an essential aspect of the manufacturing process, using engineering drawings can present several difficulties. In the two cases studied, engineering drawings caused delays in the production process and increased the time required to launch the products. These difficulties may be attributed to company processes, management, resource shortages (Matuszak 2023), and the complexity of the drawings used in the manufacturing process, which may result in errors and misinterpretations.

Moreover, the use of paper (Stateler, Harapnuik 2021) and printer ink (Kagi, Fujii et al. 2007) to create and revise these drawings is enormous, and this process needs to be more sustainable for businesses because it raises environmental concerns and issues of cost and time management. Sustainability in the industry is a concern not only for companies but also for governments and humanity in general, given the planet's global warming problems, (Dwivedi, Sassanelli et al. 2023).

Many design and manufacturing companies have a responsibility not to stay stagnant and continue using paper as a fundamental part of the processes used from the beginning of a concept through its manufacturing and the management of that product during its life cycle.

In the same direction in which manufacturing departments are making use of machine learning technology for improvement and automation from learning data collection, this practice should be followed by design offices because with the current process where the 3D and 2D are in different environments, in the best of cases within the same CAD package, it would be more difficult and complex to automate these processes.

Key performance indicators (KPIs) aid in measuring performance for key activities and initiatives. These indicators allow experts to accurately model ambiguous enterprise goals using quantitative variables with numeric ranges and well-defined thresholds. KPIs are essential tools that assist organisations in monitoring their progress towards achieving strategic objectives, making data-driven decisions, and optimising their performance. By

utilising KPIs, organisations can identify areas of improvement, track their progress over time, and make informed decisions based on real-time data, (del Mar Roldán-García, García-Nieto et al. 2021). There is an emphasis on monitoring the shop-floor process through various sensorial systems designed to collect performance data. Automated systems collect an enormous amount of performance data directly from the shop floor, providing valuable insight into the performance. The data collected by these systems can be analysed to identify areas for improvement, optimise processes, and enhance productivity. Furthermore, using these systems has enabled manufacturers to make informed decisions based on actual data rather than relying on intuition or guesswork, (Papacharalampopoulos, Giannoulis et al. 2020).

To boost their competitive edge, companies can implement the use of comprehensive 3D models for product design and process engineering, with the support of Model-Based Definition (MBD) technology within Computer-Aided Design (CAx) and Product Lifecycle Management (PLM) systems. This methodology can streamline operations, minimise errors, and enhance workflow efficiency, (Zhu, Bricogne et al. 2016).

Despite the need for further research and the numerous difficulties involved in determining a period, the findings of this study provide a positive response to the inquiry at hand: whether manufacturing companies that persist in relying on 2D drawings in a setting segregated from the 3D model will be less competitive than those that choose to implement the MBD system. This competitive disadvantage is not only linked to the creation of drawings because they will continue to be generated within the 3D model environment but also to the benefits and technological advantages of compiling all the data collected for the subsequent use of digital twins and artificial intelligence (AI). Therefore, companies that opt for the MBD system will be better positioned to leverage emerging technologies and remain competitive in the marketplace.

11 Limitations

This document has only analysed the situation of a few manufacturing companies, which makes it challenging to create a direct connection with a large number of existing companies in the world if it can be considered that only in the UK there were around 138,440 manufacturing companies in February 2023, (, Number of manufacturing companies in the UK and their Standard Industrial Classification (SIC) codes2023).

Although some companies may believe they have a robust process in place currently, it is essential to recognize that this may only be true in the present. Acknowledging that every company has distinct characteristics, including size, business model, budget, experience, and available resources is crucial. Nonetheless, this report offers valuable insights into the evolving relationship between design offices and manufacturing processes, which have yet to be fully optimised. On the other hand, companies can consider a structured approach that can be taken with expert guidance to adapt their current processes to the new technologies.

The two cases reviewed here involve companies specialising in creating personalised products for each customer. This factor significantly impacts the workflow for new product development, which should be considered when comparing these findings to those of other companies.

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