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FUTURE OF MECHANICAL ENGINEERING, MANUFACTURING ENGINEERING, AND MACHINIST ROLES FOR INDUSTRY 4.0

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Introduction

The Fourth Industrial Revolution, commonly known as Industry 4.0, is changing how products are designed and manufactured through digital transformations of cyber-physical systems. These transformations include increased automation of processes alongside the utilization of the Internet of Things (IoT) for real-time asset tracking and autonomous decision-making [1].
According to a McKinsey report, it is estimated that for manufacturers and suppliers in 2025 the value creation potential of Industry 4.0 is $3.7 trillion USD [2] even though most companies not utilizing it at scale as of now [3]. Despite this, the rate of change for the adoption of new technologies and services aligned with Industry 4.0 is increasing rapidly, supported by external influencers such as new business models, reprioritization of productand process sustainability, the Covid-19 pandemic, the disruption of supply chains, as well as government policies, standards, and regulations.

The increasing rate of change in technology development in recent years has led to concerns that the current educational system is not built to adapt and rapidly update to match the pace of industry changes, with some curriculum not having incorporated recent digitalization developments [4]. In fact, much of today's engineering education in the United States remains largely unchanged since the 1955 Grinter Report [5]. Feedback from industry suggests that skills gaps are already apparent in new entrants to the workforce and that the current curriculum is not sufficient to address these gaps [6] [7].

Current literature on the expected implications of Industry 4.0 on the future of manufacturing provides a starting point for how emerging technology will impact engineers of the future. However, current literature does not provide a holistic view of how these changes will impact workflows, how these workflows will impact the skills required, and how these changing skillsets can be met by revamping the current approach to engineering education.

The purpose of this report is to explore what typical workflows for mechanical engineers, manufacturing engineers, and machinists are expected to look like by 2030 for the United States, how these roles are shifting and converging, what skills individuals will need, and the impact educational training will play in ensuring that students and aspiring professionals of all backgrounds are developing the skills that they need to thrive in these roles.

The focus of this report is primarily on the design roles mechanical engineers fulfill, including "engineering duties in planning and designing tools, engines, machines, and other mechanically functioning equipment" or products [8]. Manufacturing engineers "design, integrate, orimprove manufacturing systems or related processes" [9] .Lastly, machinists "set up and operate a variety of machine tools to produce precision parts and instruments out of metal" including both CNC programmers and operators, and they also produce parts using newer manufacturing methods such as additive and/or hybrid manufacturing [10].

Methods

A desk research outline was created to help guide the literature search and discovery process. The literature search included academic and gray literature from 2018-2021 Strategic documents from the United States and key industry reports were identified and used to outline emerging technologies impacting future roles and responsibilities on which to focus. Academic and other gray literature was then used to supplement and support relevant insights captured. Due to the rapidly evolving nature of this topic, non- academic articles were used to further substantiate claims.

Workflows reflecting the current state for each occupation were created using information from the Occupational Information Network (O*Net), a free online database of occupational-related information specific to the United States, and Burning Glass, a job market data analytics platform. Tasks and detailed work activities were used to set out a typical workflow for each role. Required skills (sourced from O*Net, Burning Glass, the literature, and interpreted from the mapped workflows) and associated technologies were also mapped for each stage. The tasks, skills, and associated technologies that were identified are representative but non-exhaustive.

Top current skills were selected from O*Net and Burning Glass from those most requested in the last 12 months. Top growing skills were selected as the skills identified by Burning Glass with the fastest projected growth in the next two years as well as skills identified through recent literature. Since this review focused on mechanical engineers that are product designers, top technical skills such as plumbing, and HVAC were removed from the skills list. Soft skills such as “physical abilities” were also removed for mechanical and manufacturing engineers as they were outside the scope of interest for this review. Although, the skill “physical abilities” was included for the machinist role since it is relevant to insights on how machinists’ work will change in the future.

Lastly, future workflows were created from synthesizing insights from the literature on externalities driving changes in these professions and literature on emerging technologies affecting product design and manufacturing. These were then mapped onto the current workflows including identifying current tasks that would be either assisted, transformed, or replaced by emerging technologies and higher-level shifts required based on technological and non-technological externality trends. The findings presented in the future workflows and accompanying section include projections and extrapolations based on the literature findings.

Background - Current Processes and Skills

To create a baseline of current roles and responsibilities for mechanical engineers, manufacturing engineers, and machinists, workflows for the three professions were created, as shown in Figures 3.1-3.4. Figure 3.1 illustrates how the three workflows interact, moving from product development (mechanical engineering) to process development (manufacturing engineering) to implementation (machinists). Figures 3.2-3.4 provide more details via task descriptions.

Mechanical Engineer:

For the mechanical engineering role, the specific focus for this report was on mechanical design engineers. The primary responsibilities of engineers in this role are research, planning, design, development, testing, continuous improvement and redesign of new and existing products, machines, and tools, with the bulk of the work represented in the design stage, as shown in Figure 2. Although less common, some mechanical engineers also focus on strategy planning and the creation of after-sales services. Typically, a bachelor’s degree is required for this occupation (83%)

although some enter this position with an associate degree (7%) or no degree (5%) [8].Figure 5 shows the top technical skills currently requested by employers for the three roles and overlap between the occupations. Future and growing technical skills are those identified in the literature and occupational databases as becoming increasingly significant in the next 2-10 years. For mechanical engineers, new technologies are already shaping the skills that businesses are looking for with data from Burning Glass showing a growing demand, predicted over the next 2 years, for knowledge of coding, 3D modeling/design, prototyping, and engineering simulation. Additional future skills identified from the literature include experience with systems engineering,generative design, coding, simulation (including digital twin), and 3D design with a focus on aesthetics, among others. Some of the main technologies currently used by mechanical engineers are computer aided design (CAD), analytical software such as Matlab and Minitab, enterprise resource planning (ERP) software, programming tools, and financial analysis software. There is a need for engineers involved in the design phase to have knowledge of the subsequent manufacturingprocesses, with design for manufacturing (DfM) and design for assembly (DfA) skills highlighted for mechanical engineers.

Manufacturing Engineer:

Manufacturing engineers typically design, implement and improve manufacturing processes and systems (Figure 3). Most enter this role with a bachelor's degree (76%), however, it is more common than mechanical engineering to have entrants with alternative qualifications, such as an associate degree (16%) or a high school degree (4%) [9].Growing technical skills include mechanical engineering fundamentals, root cause analysis, DfM and DfA. In the short term, developing technologies appear to have less of an impact on manufacturing engineering in comparison to mechanical, with the 2-year projection showing considerable overlap with those currently requested. Manufacturing engineers will need to identify, develop, and help implement the technology required for production - to improve production times and reduce cost, waste, and defects. This will require an in-depth knowledge of new technologies such as cobots, hybrid manufacturing and IoT, and their capabilities as they become more prevalent. Currently, in addition to skills such as lean, process improvement and quality control, manufacturing engineers utilize much of the same technology as mechanical engineers, including CAD and analytical software.

Machinist:

Machinists are responsible for producing precision metal parts using machining equipment and tools, and the setup, operation, repair, and maintenance of equipment, see Figure 4. Machinists can additionally be described as CNC operators or programmers based on their primary tasks, although sometimes these terms are used interchangeably. Many entrants have a high school diploma or equivalent (36%) with others entering with post-secondary certificates (33%). A smaller proportion (17%) enter with some college credits (no degree) [10]. Both current requested skills and growing skills focus on more traditional technical knowledge, with increasingly requested skills including geometric dimensioning and tolerancing (GD&T), predictive/preventative maintenance. Working experience of engineering drawings is also required reading and interpreting to assess set-up requirements and production times and producing drawings when designing machine tools. As technology develops, understanding of hybrid manufacturing and human-cobot and AI interaction will play a larger part in this role. Working closely alongside cobots, machinists will likely be responsible for their programming and possibly maintenance of the equipment. Currently, desired machinist skills include a working knowledge of ERP, analytical and industrial control software, and CAD and computer aided manufacturing (CAM) software. Although some machinists may be involved in the design of fixtures and tools, generally the level of CAD knowledge required is less than that for mechanical and manufacturing engineering roles. Machinists also need a thorough understanding of the hardware that they use throughout the machining process.

Future Processes and Skills

Mechanical Engineers:
For mechanical engineers, user-generated data (or other real-time performance data) will be used to identify new user needs and opportunities, following more sustainable design-make-use business models in which products are designed to create feedback loops for future iterations [11]. This data can then be incorporated into digital twin design simulations for the continuous development of new products and services. For the product development stages, AI may assist engineers at each stage [12] by using historical and real-time data to provide design recommendations via generative design, resulting in better designs, higher output, and reduced risks when considering various design for manufacturing (DfM) tradeoffs [13].While simulation and generative design software will largely expedite design documentation and product development, resulting in parallel project structures (as shown in the convergence of the conceptual design, process selection, and detailed design stages below), engineers will still be required to validate inputs and outputs from models [14]. This shift will also allow mechanical engineers more time to incorporate data-backed insights into their products and services.

While not directly impacting the workflows at a high level, new manufacturing methods such as 3D printing or hybrid manufacturing may become more relevant for mechanical engineers. As 3D printing enables the fabrication of complex geometries, it pairs particularly well with generative design and may be further incorporated into various development stages such a research and development, prototyping, product customization, and repair [3]. Additionally, new tools such as AR and VR may enable a new level of stakeholder collaboration in which 3D modeled product designs can be shared and explored virtually. These shifts in workflows for mechanical engineers will require more in-depth skills for data analytics, programming, and simulation skills in addition to being able to learn and work with new technologies and interfaces [15] [16].

Manufacturing Engineers:
Manufacturing engineers will be essential in supporting the shift to Industry 4.0, shifting also their workflows and responsibilities. The IoT and AI may impact the optimization of processes via the incorporation of data into simulations for troubleshooting and continuous improvement of equipment performance, resulting in greater operational efficiencies through increased equipment utilization [17]. This data can also be incorporated into generative design for factory/equipment design, materials selection, and procurement with more emphasis in the future on sustainability considerations [14]. Additionally, manufacturing engineers will be required to have knowledge of new manufacturing methods and be able to implement them.

As noted in other articles [18] [19] AR and VR tools may shift current workflows by improving how engineers and machinists interact and support each other while also allowing for the utilization of remote specialists who can connect to specific locations tooffer assistance at a systems-level while allowing for the specialists' capabilities to connect to multiple locations [18].

A recent survey commissioned by the Institute of Mechanical Engineers (IMechE) and the Institute of Engineering Technology (IET) on the future manufacturing engineer found that 84% of respondents believed automation, robots, and mechatronics will be the most important knowledge and skills for manufacturing engineers to havein the next ten years. AI was second with 69% of respondents in agreement, while lean principles/sustainable manufacturing was ranked third (65% of respondents) [20].

Machinists:
One drastic shift in future workflows can be seen for machinists, specifically CNC operators. Through the incorporation of robots and/or cobots into most of the workflow stages, the role of CNC operators, compared to current workflows, is dramatically reduced. In contrast, the roles of traditional CNC programmers will be augmented through the incorporation of new technologies such as hybrid manufacturing, 5-axis machining, and robots which will require integration into current processes and troubleshooting [21]. More downstream, machinists' workflows and job descriptions will be impacted by the IoT and AI through in-line quality checks and rapid correction [3]and asset/equipment tracking and maintenance, further increasing efficiencies by reducing waste and minimizing machine downtime [22]. Tools such as AR and VR may additionally be used for training and assistivepurposes [15].Another shift for machinists of the future may include moving from task-based workers who mainly produce parts to knowledge-based workers who can take a more active role in process improvement, and quality control and assurance. This includes things like increased creative fixture and tooling design using CAD, supporting the transition to automation, and working with new technologies that assist with quality assurance andquality control. This would require additional training with an emphasis on critical thinking, problem-solving, CAD, programming, and data analysis skills.

Impact of Education and Training

There is a strong interest in improving engineering education through dedicated courses in Industry 4.0 subjects and skills. To close the skills gaps identified above, post-secondary institutions need toupdate their curriculum to prepare students for the roles and responsibilities within Industry 4.0. Many programs look towards accreditation to ensure quality and continuous improvement of their programs. In the US, programs are accredited by the Accreditation Board for Engineering and Technology (ABET). ABET is a nonprofit, nongovernmental organization with ISO 9001:2015 certification, which primarily accredits college and university programs in applied sciences, computing, engineering, and engineering technology. The aim of this accreditation is to ensure thatthe program meets an educational standard that prepares graduates to enter the global workforce [23].

Part of continuous curriculum improvement includes replacing or revamping classes to allow the development of skills needed for future roles. A literature review of the current curricula reveals a heavy emphasis on engineering fundamentals such as mathematics and physics, with less focus onemerging tools and technologies. To create space for the academic curriculum to incorporate new technological tools and processes, engineering education will need to reduce heavy emphasis on areas such as mathematics, while still maintaining rigor in engineering fundamentals, to ensure development of future technical and soft skills. Current leaders in engineering education have shifted curriculums towards more hands-on, multidisciplinary project-based learning to help students apply their technical knowledge while developing important soft skills such as communication and teamwork [24].

Many universities are now following suit and have already begun to integrate an increased number of client-facing and/or industry relevant project-based classes in their programs. For example, Arizona State University (ASU) in the US currently has eight project-based classes from a total of 40 classes in their manufacturing engineering degree program. It is expected that future jobs will require strong cognitive skills such as creativity, problem-solving, critical thinking, alongside communication skills, teamwork and adaptability [25]. Hence, it is essential that allprograms make this shift towards project-based learning, ideally with industry clients and real- world problems, to ensure effective skill development.

Though it is often expected that extracurriculars will bridge the gap between what is learned in class and how it is applied, academia should aim to teach all future skills through the core curriculum. This will allow students to strengthen skills already taught through new applications inextracurricular activities, as well as have the chance to explore other areas of interest. It is also important to note that not all university have the same resources to accommodate extensive extracurricular activities, making it especially necessary that the core curriculum cover all relevant skills.

As adoption of new technology and tools become more prevalent, it is expected that academia will adopt a blended learning environment (in-person, complemented by digital learning) to create accessible education channels for both current students and for those looking to upskill or reskill. Students will be able to use several online platforms, ranging from cloud-based collaboration platforms to simulation tools, to strengthen learning outcomes and encourage teamwork. For the current workforce specifically, reskilling and upskilling is increasingly important as tools and technologies rapidly change for Industry 4.0. To accommodate and encourage this, academia needs to shift towards lifelong learning programs in the form of digital offerings, many of which may be short courses or bootcamps allowing the current workforce to learn part-time while still continuing to work. Similarly, shorter programs for hands-on training, such as apprenticeship-type programs or work-based learning must be offered to allow for practical skills to be developed [24]. These shifts in education will ensure that those in the current workforce, as well as those entering the workforce in the future, have accessible ways to develop skills needed for Industry 4.0.

Conclusion

Advancements in technology, improved data connectivity, the evolution of Industry 4.0, along with societal and cultural shifts are changing how products are designed and manufactured. This will require engineers to develop new skill sets through enhanced training methodologies to keep up with the fast pace of changing technologies. This literature review aimed to explore what typical workflows for mechanical engineers, manufacturing engineers, and machinists are expected to look like by 2030 in the United States. This review also explored how these roles are shifting and converging, the skills these roles will need, and the impact education will play in ensuring that students and aspiring professionals of all backgrounds are developing the skills that they need to thrive in these roles.

Key findings for each section include:

- Key technologies expected to be most relevant in the future include: Internet of Things (IoT), Artificial Intelligence (AI), Augmented Reality (AR) / Virtual Reality (VR), simulation software (e.g., digital twin), generative design, and robots/collaborative robots (cobots).
- Future workflows are shifting from linear to parallel and iterative, as data will drive faster and more effective decision making. This will allow for greater flexibility, higher operational efficiencies and quality while reducing risks. Future workflow success will require cloud-backed software to connect all three roles via a single data model, helping to connect, share, and streamline the processes while breaking down information silos. Access to data will allow for better visibility across design, manufacturing, and implementation processes allowing for more informed decision making.

- Future mechanical engineers will require more advanced skills in data analytics, programming, simulation (including digital twin), systems engineering, and Design forManufacturing (DfM), in addition to being able to quickly learn and work with new technologies.
- Future manufacturing engineers will require skills in automation and AI as they support thedigitalization and optimization of manufacturing processes.
- Future machinists will shift from task-based workers who mainly produce parts to knowledge-based workers who can take a more active role in process improvement andquality control/quality assurance, requiring additional skills such as critical thinking, problem-solving, CAD, programming, and data analysis.
- These three roles will require specific soft skills in the future including multidisciplinaryand cross-cultural collaboration, communication, empathy, and creativity skills.
- Academia needs to work with industry to revamp current curriculums at post-secondaryinstitutions to align what is being taught with anticipated skills (technical and soft) for Industry 4.0. This can be accomplished through more experiential learning (e.g., client interactions, project-based learning, work terms, apprenticeships, etc.)
- Shorter programs focusing on specific skills can be used to upskill or reskill employees forfuture or upcoming job needs in accessible settings (e.g., part-time offerings, blended mediums that include digital and in-person courses, etc.)
- Academia needs to implement new credentialing methods, such as micro credentials in theform of digital badges, to recognize technical and soft skill development not typically recognized within core curriculum through transcripts. Industry also needs

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FIGURES

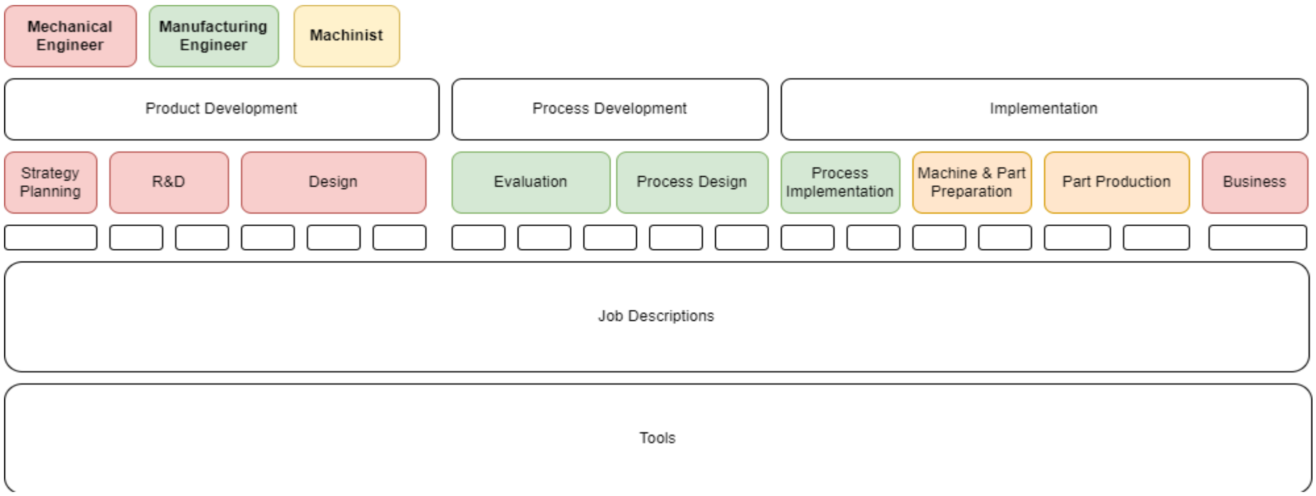

Figure 1. High-level interaction and progression of mechanical engineering, manufacturing engineering, and machinist workflow

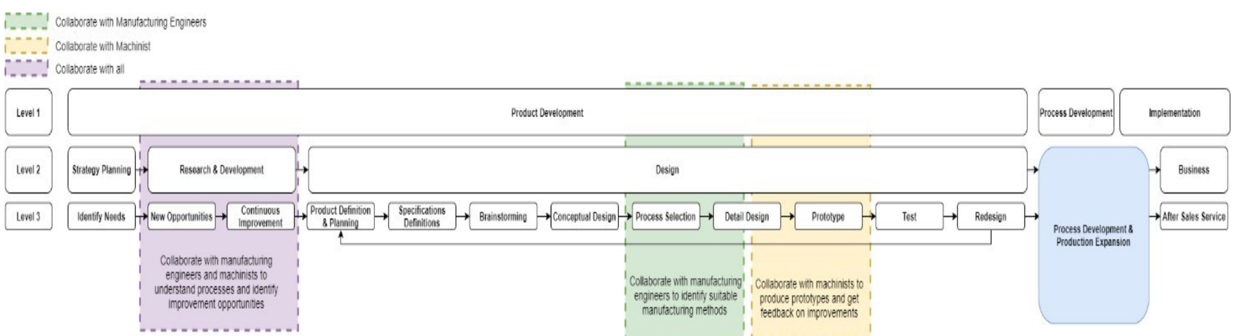

Figure 2. Current mechanical engineering workflow

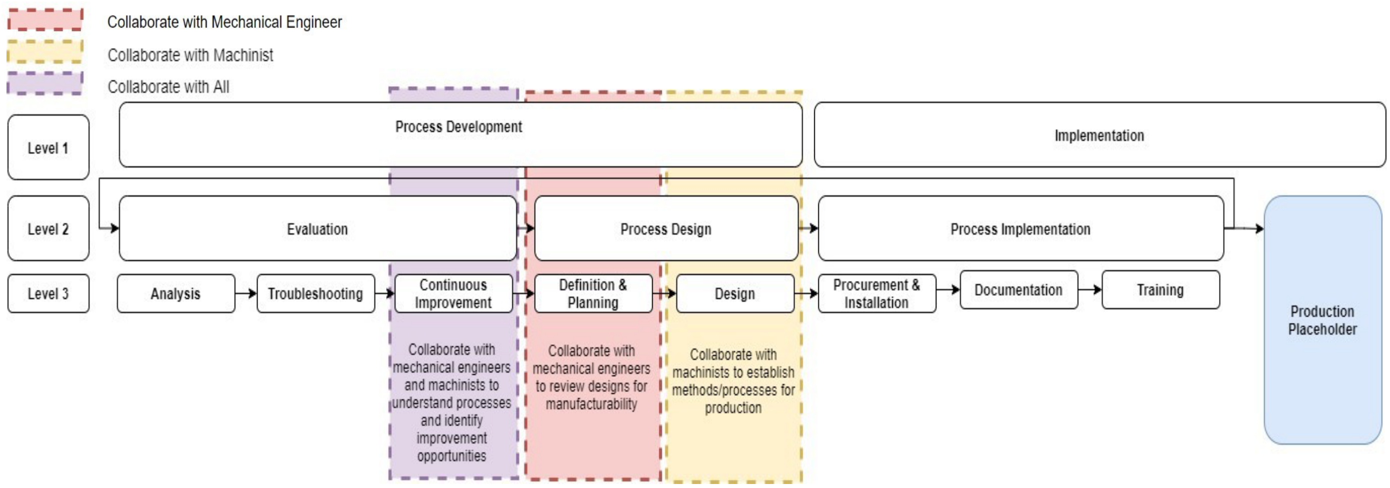

Figure 3. Current manufacturing engineering workflow

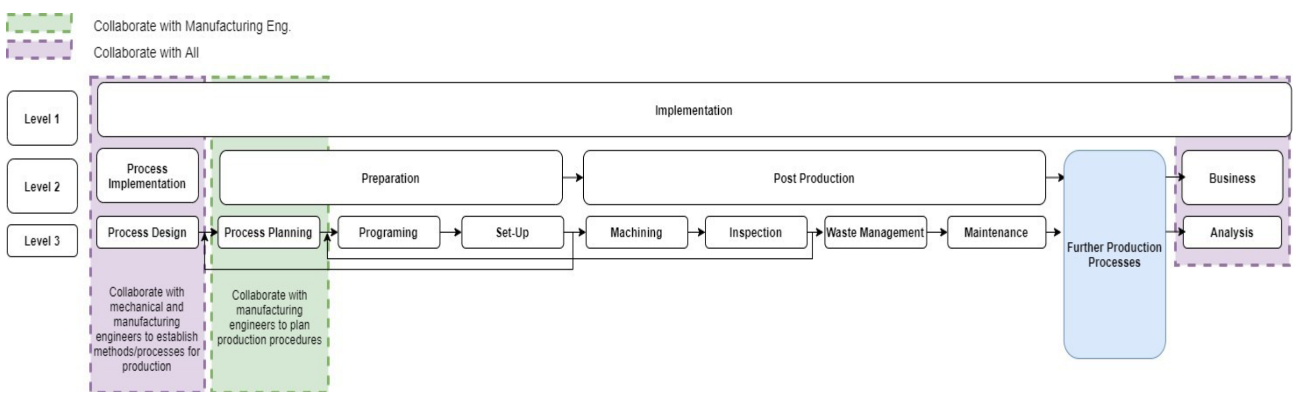

Figure 4. Current machinist workflow

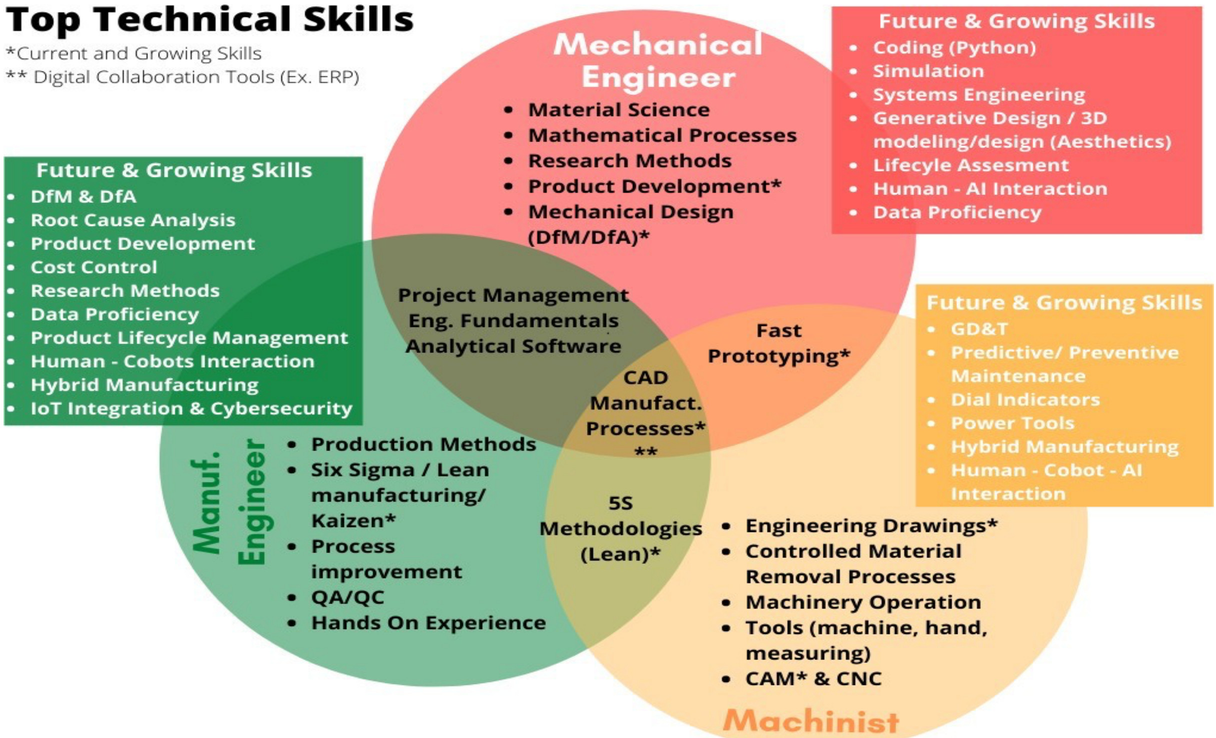

Figure 5. Top current and growing technical skills for mechanical engineers, manufacturing engineers, and machinists