Universidade do Minho
Escola de Engenharia

Acendino Alves da Silva Neto

Technological Evolution in Machining Processes with CNC Machines in the Context of the Concept of Industry 4.0

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Dr. Fernando Carlos Cabrita Romero

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Nome: Acendino Alves da Silva Neto

Endereço eletrónico:acendino_alves@hotmail.com Telefone:+351934658925

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ABSTRACT

The work related to the project of this dissertation will consist of an analysis of the technological evolution of the machining processes with CNC (Computer Numerical Control) machines regarding the new concept of Industry 4.0. The concept fits into the current transformation process for the fourth industrial revolution, such as integrated Cyber-Physical Systems (CPS) within the manufacturing processes using the Internet of Things (IoT) in industrial processes. Faced with technological advances, the processes of Industrial Engineering in machining using CNC machines must undergo adaptations, aiming at substantial increases in the operational effectiveness. Thus, an approach will be made to understand how current processes can adapt to the concept under study when analyzing the evolution of the machining tools for CNC machines in the face of new processes. A thorough study will be done to adapt the methodology of Industry 4.0 applying it to the machining processes in CNC Machines. Thereby, a proposal for future applications will be given on the topics studied. The methodology will be based entirely on a documental analysis research strategy.

The virtual technology in machining tools is still a subject in development, being one of the main factors to be understood in this dissertation. In this study, it will be possible to analyze the main factors that can influence directly or indirectly the production processes of a factory with CNC machines. It will be explored and studied the types of machining processes for CNC machines and the types of machining tools developed with virtual technology.

When we are talking about virtual technology, we are usually addressing the need for software. In CNC machining operations, there is a CAM (Computer Aided Manufacturing) software that performs machining simulations for CNC machines. Thus, a study and analysis of a production system involving a CAM software, a tool with virtual technology and CNC machines will be done to verify how this set can work encompassed and what changes this production model introduces. In the sequence of this study, an idea of a new production system will be proposed, allowing for a better understanding of the possibilities for application of new approaches in the future.

KEYWORDS

CNC Tools; CNC (Computer Numerical Control); CAM (Computer Aided Manufacturing); CPS (Cyber-Physical System); IoT (Internet of Things); Industry 4.0

RESUMO

O trabalho relacionado ao projeto desta dissertação de mestrado consistirá de uma análise da evolução tecnológica dos processos de usinagem com as máquinas CNC (Comando Numérico Computacional) em relação ao novo conceito da Indústria 4.0. O conceito se enquadra no atual processo de transformação da quarta revolução industrial, com os Sistemas Ciber-Físicos integrados (CPS) dentro dos processos de fabricação que utilizam a Internet das Coisas (IoT) em processos industriais. Diante dos avanços tecnológicos, os processos de Engenharia Industrial em usinagem utilizando máquinas CNC devem sofrer adaptações, visando um aumento substancial na eficácia operacional. Assim, uma abordagem será feita para entender como os processos atuais podem se adaptar ao conceito em estudo, visando também uma análise da evolução das ferramentas de usinagem para máquinas CNC em face de novos processos. Um estudo minucioso será feito para adaptar a metodologia da Indústria 4.0, aplicando-a aos processos de usinagem em máquinas CNC. Com isso, algumas proposta para aplicações futuras serão apresentadas para os tópicos estudados. A metodologia será totalmente baseada em uma estratégia de investigação documental.

A tecnologia virtual em ferramentas de usinagem ainda é um assunto em desenvolvimento, sendo um dos principais fatores a serem compreendidos na realização deste trabalho. Neste estudo, será possível analisar os principais fatores que podem influenciar direta ou indiretamente nos processos de produção de uma fábrica com máquinas CNC. Serão explorados e estudados os tipos de processos de usinagem para máquinas CNC e os tipos de ferramentas de usinagem desenvolvidas com tecnologia virtual. Quando abordamos o assunto sobre tecnologia virtual, geralmente estamos a lidar com a necessidade de um software. Nas operações de usinagem CNC, existe um software CAM (Manufatura Assistida por Computador) que realiza simulações de usinagem para máquinas CNC. Assim, um estudo e análise do sistema de produção envolvendo um software CAM, uma ferramenta com tecnologia virtual e máquinas CNC será feito para verificar como este conjunto pode trabalhar englobado e quais as mudanças para esse modelo de produção. Na sequência dessa análise, será proposta uma ideia de um novo sistema de produção, que permite uma melhor compreensão das possibilidades de aplicação no futuro das novas abordagens.

PALAVRAS-CHAVE

CNC (Controlo Numérico de Computadorizado); CAM (Manufatura Assistida por Computador); CPS (Sistema Cibernético Físico); IoT (Internet das Coisas); Indústria 4.0

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Nomenclature and Abbreviation

Nomenclature

$\boldsymbol{V_C}$ - Feedrate in meters per minute

$\boldsymbol{D}$ - Diameter of the cutter

$\boldsymbol{n}$ - Speed in rotation per minute

Abbreviation

API - Application Programming Interface

BOM - Bill of Materials

CAD - Computer Aided Design

CAM - Computer Aided Manufacturing

CNC - Computer Numerical Control

CPPS - Cyber-physical Production Systems

CPS - Cyber-Physical Systems

CPU - Central Processing Unit

CS - Cyber System

DNC - Direct Numerical control

IC - Integrates Circuit

ICT - Information and Communication Technology

IoS - Internet of Services

IoT - Internet of Things

IPv4 - Internet Protocol version four

IPv6 - Internet Protocol version six

ISO - International Organization for Standardization

M2M - Machine-to-Machine

MIT - Massachusetts Institute of Technology

NC - Numerical Control

PCB - Printed Circuit Boards

PLC - Programmable Logic Controller

PS - Physical System

RFID - Radio-Frequency Identification

USA - United States of America

USB - Universal Serial Bus

1. INTRODUCTION

1.1 Framework and objective

The work related to the project of this dissertation will consist of an analysis of the technological evolution of the machining processes with CNC (Computer Numerical Command) machines regarding the new concept of Industry 4.0. The concept fits into the current transformation process for the fourth industrial revolution, such as integrated Cyber-Physical Systems (CPS) within the manufacturing processes using the Internet of Things (IoT) in industrial processes. This dissertation has the following specific objectives:

1) Adapt the methodology of Industry 4.0 applying it to the machining processes in CNC Machines.
2) Study of the issues related to the technological evolution of the tools used in CNC's with virtual technology.
3) Explore and study the types of machining processes for CNC machines and the types of machining tools developed with virtual technology.
4) Study and analysis the production system between a CAM software, a tool with virtual technology and CNC machine.
5) Develop proposals for future applications and enhancements on the studied topics.

Currently, governments around the world are initiating programs to ensure competitiveness through adaptation to digital transformation (Kagermann, Wahlster & Helbig, 2013). In order to carry out this project, a detailed analysis of numerous primary, secondary and tertiary literary sources will be carried out in relation to the proposed topic related to Industry 4.0 and the principles it approaches, correlating it with the machining processes in CNC machines and with operation tools with virtual technology, which are currently under development. As such, scientific articles, books, and dissertations addressing the topic related to the purpose of this work will be researched and analyzed. Subsequently, with the conclusion of the archival research, all the relevant information will be synthesized in a critical review of the literature - so that it is possible to develop a complete and detailed knowledge and understanding regarding the proposed theme.

Simultaneously and in parallel, in order to reach the first objective of this dissertation, a thorough study will be done to adapt the methodology of Industry 4.0 applying it to the machining processes in CNC Machines. For this study, it will be necessary a research and an analysis of scientific articles, books, and dissertations, which contain research related to the Industry 4.0 and subjects related to the technological evolution of the tools used in CNC Machines with virtual technology, aiming at the improvement of the machining processes. With the knowledge acquired, a framework will be established between the methodology of Industry 4.0 and the machining processes, in order to present a better opportunity of execution in the machining processes for CNC machines. For the development of this first objective it will be crucial the knowledge of the methodology of Industry 4.0 and the processes of machining with CNC Machines.

In the next phase, we know that one of the main factors that influence the development of machining processes in CNC machines are the tools used in CNC machining processes for the production of pieces or similar artifacts. Therefore, for the development of the second objective, a deep study of the issues related to the technological evolution of the tools used in CNC's with virtual technology will be necessary. The virtual technology in machining tools is still a subject in development, being one of the main factors to be understood in this work. In this study, it will be possible to analyze the main factors that can influence directly or indirectly the production processes of a factory with CNC machines. After all, the communication system between the tool and the machine will be totally virtual, having greater precision regarding the wear and friction information about the tool, working more efficiently with a system included between CNC machine, tool, and software - where human intervention to check whether the quality of the tool is good or not will not be necessary or it will be greatly reduced. Thereby, a study of the impact of human labor will be done.

Considering that the requisite "CNC machining tools" is one of the main factors that can affect, beneficially or not, the execution of machining processes in the CNC's, and in order to carry out the third objective presented in the objectives of this dissertation, it will be explored and studied the types of machining processes for CNC machines and the types of machining tools developed with virtual technology. In this part of the dissertation an analysis of how the machining operations (drilling, milling, turning, etc.) may undergo modifications in the execution will be made, emphasizing tools with virtual technology.

When we are talking about virtual technology, we are usually addressing the need for software. In CNC machining operations, there is a CAM (Computer Assisted Manufacturing) software that performs machining simulations for CNC Machines in a not very efficient way, because there is an immense need for the programmer's knowledge, in view of the type of CNC Machine, tools, what kind of workpiece material and production data (cutting speed, RPM, cutting feed, etc.) - where all this information is transmitted to the software by the programmer.

If there is any incorrect information or if it is not according to the type of material, or if there is non-ideal machining data, there will be a direct impact on the execution of the machining process. Therefore, the fourth objective of this dissertation will study and analyze the production system between a CAM software, a tool with virtual technology and CNC machine to verify how this set can work encompassed and what changes to this new production model. In order to analyze how this encompassed communication can work more efficiently without the immense need of the programmer's knowledge. That objective will be integrated on the concept of Industry 4.0 to achieve the main objective as mentioned above. Thereby, during the development of this work, it come up an idea of a new production model, and this idea will be proposed, which involves an architecture, development, identification of advantages in production, considerations on the impact in human labor and it will present the challenges of implementation for better understanding the possibilities for application in the future. So, as the last objective of this dissertation, some proposals for future applications concerning the suited topics will be suggested.

In chapters 2, 3 and 4 a literature review of the main concepts will be made to acquire a better understanding for the development of the objectives in this dissertation. Chapter 5 addresses the adaptation of the methodology of Industry 4.0 applying it to the machining processes in CNC Machines. In Chapter 6, a proposal will be suggested to have a better process production for future applications in machining processes in CNC machines succeeding the methodology of Industry 4.0. Chapter 7 aims to study how a CAM software works in communication between the tool with CPS and a CNC machine, presenting the CAM possibilities of connection and effects. Chapter 8 proposes an idea of how a new method of measurement could be done by the CNC tool with CPS during the process execution. Chapter 9 will explore and analyse how the production system works encompassing the tool with CPS, the CNC machine, a CAM software, and the concept of Industry 4.0. Finally, Chapter 10 presents a general proposal for a new production model and a better production system for machining areas. This final proposal will show how this new production model could work integrating the tool with CPS, CNC machines and CAM software in a better way than existing models, and will show the new idea of communication interaction between them.

1.2 Methodology

The methodology used during the development of this dissertation was based entirely on a documental research strategy. The bibliographic research was based in scientific publications on the machining area, machining processes, CNC machines, CAM and CAD software and the context of Industry 4.0. A new tool with cyber-physical technology has emerged in the CNC machining area, a technology with a combination of sensors, algorithms, the cloud, data analysis, and connectivity with Internet of Things (IoT), has provided the focus for this study, in order to highlight what changes could be done on actual processes on CNC machines.

The methodology of this dissertation also has been based on the author´s experience of programming and operation of CNC´s machines during his eight years of experience with machining processes engineering. Through it, the topics addressed in this dissertation were compared to the problems experienced by the author to suggest what the changes could be done to future applications in the context of Industry 4.0. In this sense, data collection methods for this research involves also observation, and primary data, besides the collection of secondary data from documental sources. So, a detailed analysis of numerous literary sources has been carried out in relation to the proposed topic related to the context of Industry 4.0 and the principles it approaches, correlating it with the machining processes in CNC machines and with operation tools with virtual technology, which are currently under development. All the relevant information was synthesized in a critical review of the literature.

The study done to adapt the methodology of Industry 4.0 applying it to the machining processes in CNC machines was based on scientific articles, books, and dissertations, which contained research related to the Industry 4.0 concept and subjects related to the technological evolution of the tools used in CNC Machines with virtual technology.

The study of the issues related to the technological evolution of the tools used in CNC's with virtual technology has been made through scientific publications and the information given by the company´s developer, Sandvik, through the catalogue and site. The virtual technology in machining tools is still a subject in development, being one of the main factors to be understood in this work.

Research on the types of machining processes for CNC machines and the types of machining tools developed with virtual technology has been made through scientific publications and books about machining processes and CNC machines, having in mind how the machining operations may undergo modifications, emphasizing tools with virtual technology.

The research on the production system integrating a CAM software, a tool with virtual technology and CNC machines, was made to verify how this set can work together and what changes it implies. The research has been made through scientific publications and books.

The proposals suggested by the author on the following chapters, concerning improvements in CNC machines, software and production model, were developed based on the author´s knowledge acquired during his experience, and on the documental research made during the development of this dissertation.

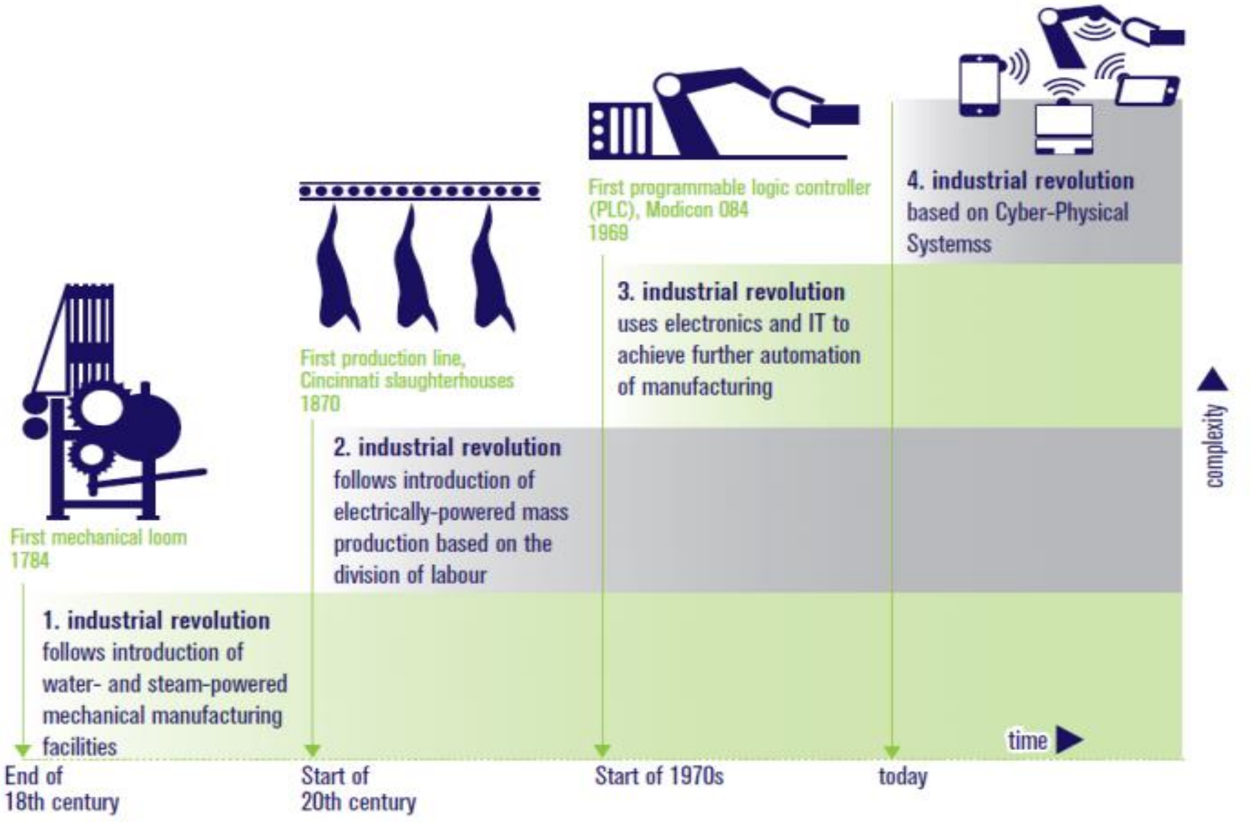
2. LITERATURE REVIEW: INDUSTRY 4.0

This chapter presents the main concepts studied and analyzed about the Industry 4.0 paradigm to carry out the necessary research for this master thesis.

2.1 The Concept of Industry 4.0

The concept fits into the current transformation process for the fourth industrial revolution, such as integrated Cyber-Physical Systems (CPS) within the manufacturing and logistics processes using the Internet of Things (IoT) and the Internet of Services (IoS) in industrial processes (Platform Industry 4.0, 2017). The definition of the term Industry 4.0 was first presented in 2011 by the famous Hannover Fair as a project in the High-Tech Strategy of German Industry (Hermann, Pentek & Otto, 2015). Shortly thereafter, in the year 2013, the German working group presented a report about Industry 4.0 (Hermann et al., 2015). The report defined the environment for Industry 4.0, which included a strong customization of the products obtained with high flexibility of mass production (better technology in automation), presenting an introduction of the methods of systems with own organization (own automation, own configuration, own diagnosis, etc.) to obtain an adequate connection between the real world (people and machine) and the virtual world (Devezas, Leitão & Sarygulov, 2017). This new era of industry is centered on the intensive use of advanced Information and Communication Technology (ICT) resources in order to ensure greater flexibility in production systems and processes, as a consequence the increasing complexity of products and supply chains (Faller & Feldmüller, 2015).

The industrial revolutions are characterized by radical changes, motivated by the incorporation of technologies, which is reflected in the economic, social and political field. Until nowadays the consensus was that there were three industrial revolutions. The first occurred between the years of 1760 and 1840, dominated by technologies such as steam and hydraulic machines, and has as a symbol of this phase there was the advent of the first automated machining loom and other textile machinery. The second revolution took place between the late nineteenth and early twentieth centuries, represented by the introduction of electricity, the assembly line and the emergence of production based on a high, accentuated division of labor. The third stage of industrialization began around the 1960s, and is marked by the development of semiconductors, and technologies such as mainframes and personal computers. It was the age of the emergence and diffusion of electronics and information and communication technologies (ICTs), which later in the 1990s saw the emergence of the Internet (FDC, 2016). **Figure 1** briefly shows the succession of revolutions and characterizes each one.



Source: (Kagermann et al., 2013)

Figure 1: Phases of Industrial Revolution.

This new paradigm of the industry has as main purpose which is the consolidation of intelligent factories. It highlights the dissemination of Cyber-Physical Systems (CPSs), the evolution of embedded systems, allowing the implementation of the Internet of Things (IoT) and Services (IoS), making each input, feature or product a network-connected and mappable object. Cyber-Physical Systems correspond to the evolution of embedded systems in the form of devices distributed and connected to wireless networks with the ability to communicate with each other and with the Internet. That results in the convergence between the physical and virtual world (cyberspace). Accompanying this movement is the enhancement of network protocols such as IPv6, which provides enough network addresses to allow connectivity with intelligent objects via the Internet. This fact enables the conditions for the creation of the Internet in which resources, information, objects and persons will be connected in specific and particular ways. This technological evolution affects industry, and in the scope of manufacturing is described as the fourth stage of industrialization, or Industry 4.0 (Kagermann et al., 2013).

The main purpose of Industry 4.0, enabled by the convergence and integration of emergent and new technologies, is the creation of smart factories. These are capable of managing process complexity, operate with less disruption, and more efficiently. The interaction between humans, machines and resources resembling a social network (Kagermann et al., 2013) as you can see in **Figure 2**. In these installations, cyber-physical systems monitor physical plant processes and make decentralized decisions. Physical systems are converted into objects of the Internet of things, communicating and collaborating with each other and with humans in real time through wired and wireless networks connected to the Web (Marr, 2016).

Source: (Gigamon, 2017)

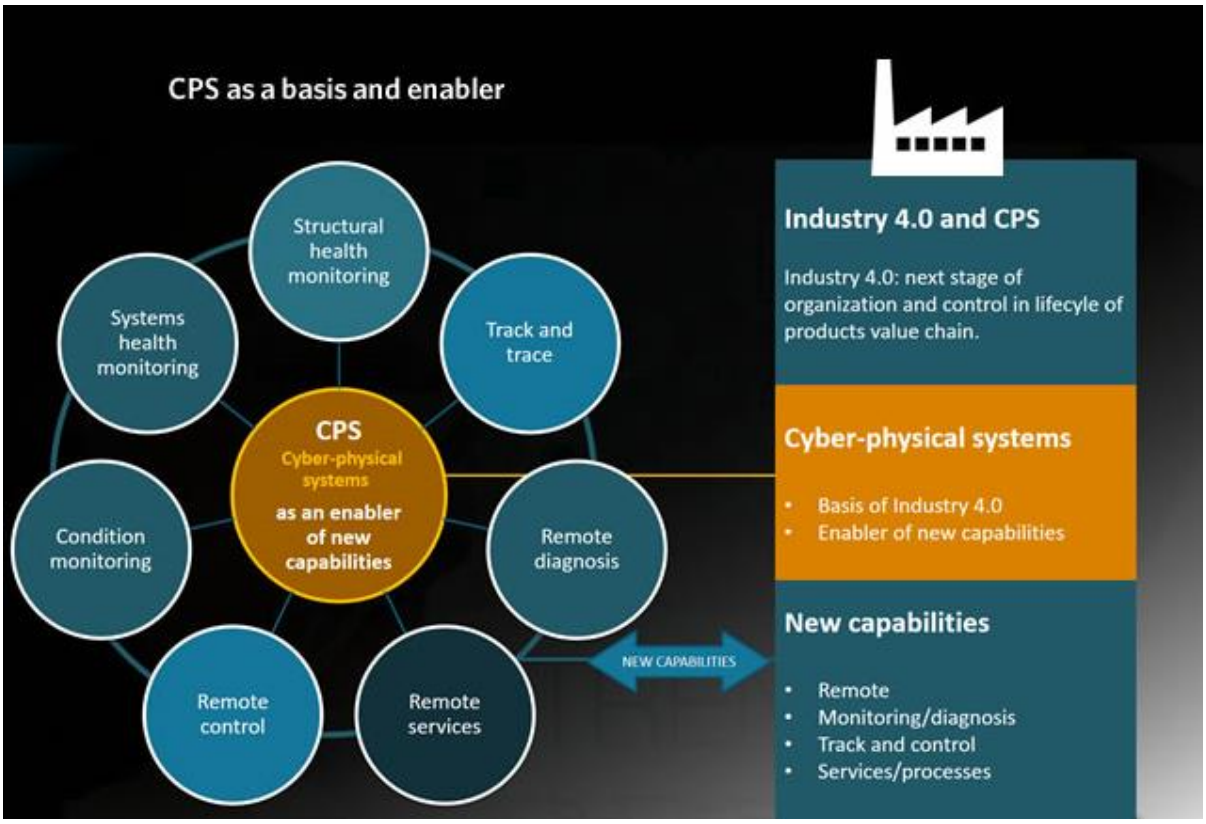
Figure 2: Smart Factories on Industries 4.0.

2.2 Cyber-Physical System (CPS)

In the general conception of CPS, it is a system formed by collaborative virtual entities intensely connected to the physical world and their processes in progress and interaction, consuming and providing access to data and data processing services available on the Internet (Acatech, 2011). According to the Report of the Steering Committee for Foundations and Innovation for Cyber-Physical (NIST, 2013), CPS´s have a great potential for modifying various aspects of life, allowing the development of concepts such as autonomous cars, robotic surgery, intelligent buildings, intelligent electrical network, intelligent manufacturing and implanted medical devices.

Specifically, in the scope of manufacture, Cyber-Physical Systems (CPS) correspond to the physical and virtual systems in an integrated network that brings together physical resources and processes (Gorecky, 2014). In these networks multiple information from different sources circulates that is monitored and synchronized between the factory and cyberspace (Lee, Bagheri

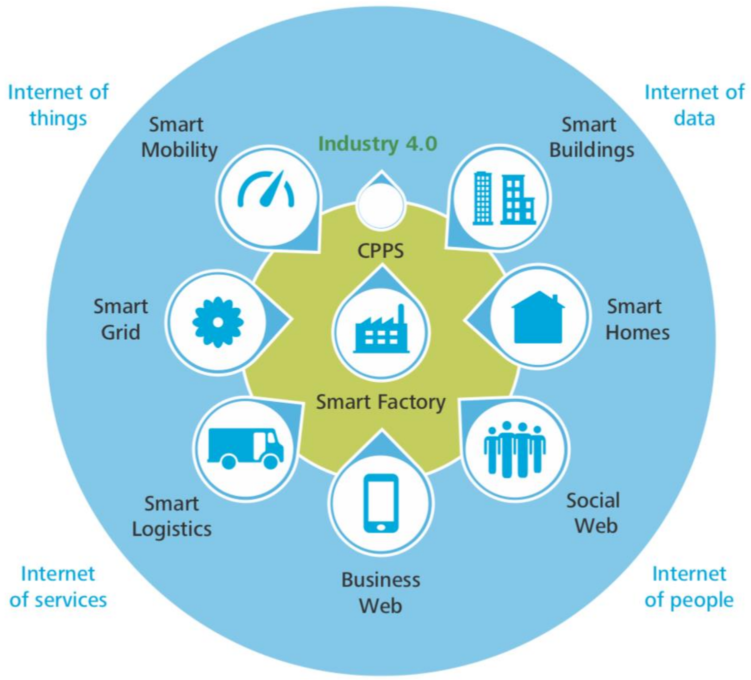
& Kao, 2015). The intelligent CPS, machinery and installations are able to exchange information autonomously, perform drives and control to others independently (Kagermann et al., 2013). According to Macdougall (2014), cyber-physical systems create the conditions for Internet of Things (IoT) which are combined with Internet Services (IoS) for Industry 4.0. The interaction between systems based on high-performance software and dedicated user interfaces, integrated with digital networks, creating a new universe of functionalities for systems, making CPS simultaneously a basis and enabler, as represented in **Figure 3**. Thereby, the CPS´s represent a paradigm shift from business models and the development of new applications, services and value chain.



Source: (I-Scoop, 2016)

Figure 3: CPS as a basis and enabler.

One of the concepts of Cyber-physical Systems is the Cyber-physical Production Systems (CPPS). These consists of machines, warehouses, logistics and intelligent production facilities that have been digitally mapped and enable the end-to-end integration of ICTs, from inbound logistics to outbound logistics and services, through production and marketing (Kagermann et al., 2013). It also has the function of enabling communication between machine, human and products as the example in **Figure 4** shows. Elements of a CPPS will be able to acquire and process data, to self-control certain tasks and interact with humans through interfaces (Monostori, 2015).



Source: (Ecosystems 4 innovators, 2016)

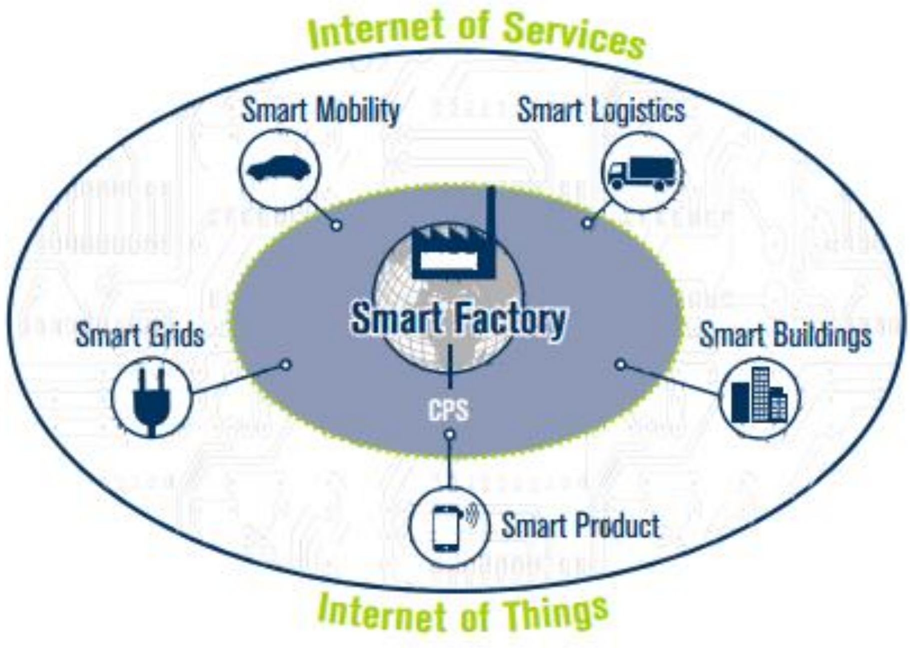
Figure 4: CPPS as a data processor.

2.3 Smart Factories

The main objective of Industrial 4.0 is to consolidate the "Intelligent Factories" concept to allow the customized on demand products and services according to the necessity of consumers (Pisching et al. 2015). As Deloitte (2017) argues, the smart factory is a flexible system that can self-optimize performance across a broader network, self-adapt to and learn from new conditions in real or near-real time, and autonomously run entire production processes.

The fusion of physical and virtual worlds through cyber-physical systems and the concomitant fusion of business processes and technical processes are opening the way for a new industrial era synthesized by the concept of "Smart Factory", which falls within the scope of the Industry 4.0 strategy.

The implementation of Cyber-physical systems in systems of production makes the concept of "intelligent factories" emerge. High levels of automation are applied in intelligent factories. This is possible because of flexible networks of production systems based on cyber-physical systems, supervising processes automatically. Flexible production systems, which are capable of responding in almost real time, allow the internal production processes to be radically optimized. The production advantages are not limited or constrained to exclusively one production unit. They can also be optimized according to a global network of adaptable and self-organizing production units belonging to more than one operator **Figure 5** (Macdougall, 2014).



Source: (Kagermann et al., 2013)

Figure 5: Smart Factory in Industry 4.0.

2.4 Machine-to-Machine (M2M)

The two major elements that enable to change the manufacturing environment to what is called Industry 4.0 is Machine-to-Machine (M2M) communication in combination with the Internet of Things (IoT). The concept of Machine-to-Machine (M2M) refers to communication between the machines with computerized capacity and communication without necessity of human intervention (Kim, 2014).

The data created by these machines could be saved and used by an application of useful data. The M2M communications are used for automated data transmission and measurement between mechanical or electronic devices. Typical components of an M2M system are: field deployed, wireless devices with embedded sensors or RFID and Wireless communication networks (Advantech, 2015).

A M2M service forms a Cyber-Physical system (CPS) where data is coming from sensors of physical machines and is analyzed, then converted to a value in a cloud computing environment (a cyber space). The data consequently becomes part of "Big Data" and data analytics and optimization can be performed, being now one of the main issues in information technology and service science communities. Recently, M2M service has attracted increasing attention from business and innovation perspectives in scientific and technological communities. A remote maintenance system using M2M communication is a typical and commercially successful application (Uchihira, Ishimatsu, Sakura, Kageyama, Kakutani, Mizushima & Yoneda, 2015).

2.5 Internet of Things (IoT)

The Internet of Things (IoT), is considered as an emergent technological wave in the global information industry. According to Chen, (2014), IoT is a network that connects all things to the Internet for the purpose of exchanging information and locating devices through pre-established protocols. IoT achieves the goal of promoting an intelligent identification, tracking and managing things. It is the extension and the concept of an Internet based on networks, which expands the paradigm of people to people, and things, or between things and things.

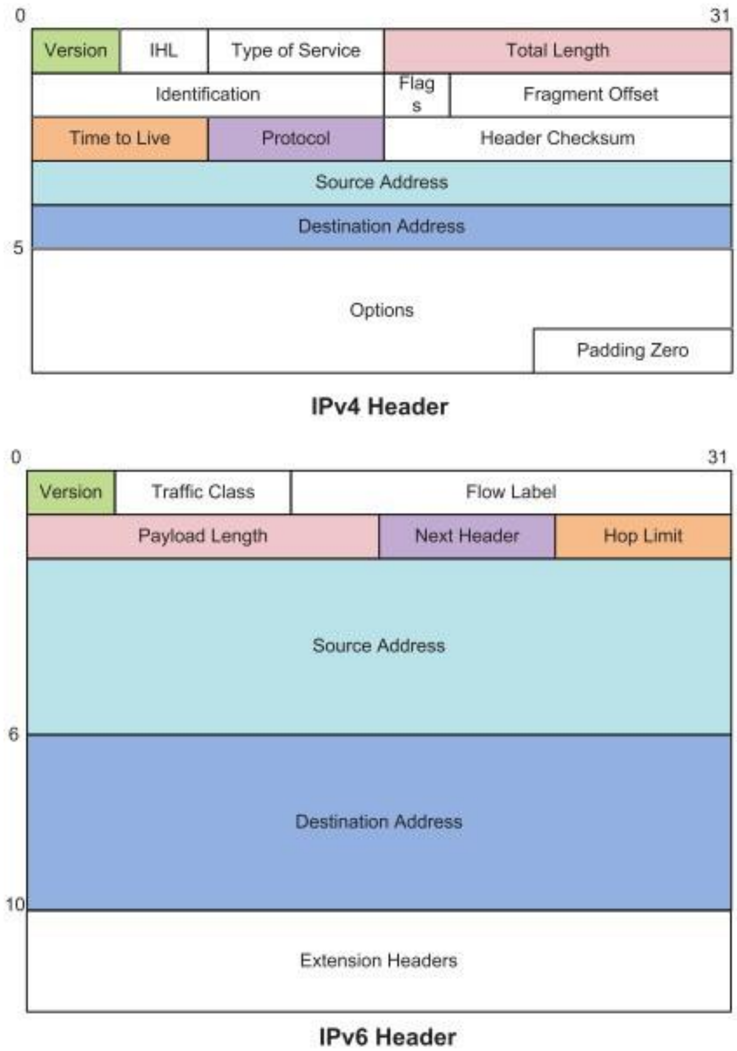
There is no final and absolute definition for IoT, since experts in the field have different perspectives on the subject. However, following expected technological evolution, it is possible to identify some characteristics that IoT should have (Chen, 2014):

- Comprehensive Perception - Using RFID, sensor, and barcode resources for information anywhere, anytime. From this perspective, communication systems and information will be incorporated imperceptibly and naturally in the environment. The networks will allow people to interact remotely with the real world.
- Reliable Transmission - A set of technologies for radio networks, telecommunication networks and the internet will allow the transmission and availability of information between network objects at any time. IoT creates the interaction between the physical world, the virtual world, the digital world and society.
- Intelligent Processing - will support IoT applications by collecting data for databases, various intelligent computing technologies, including cloud computing. Network service providers can process a large volume of messages instantly through cloud computing. Thus, this technology will be the promoter of IoT.

2.6 Internet Protocol version 6 (IPv6)

The Internet Protocol (IP) is the most widely used communications protocol because it is the most pervasive communication technology. The protocol known as Internet Protocol version 4 (IPv4) has been the protocol used for the initial stage of the Internet, and currently is almost extinct, due to the demand for use (Wu, 2013). Initially, IPv4 was designed to support just over 4 billion IP addresses, due to its 32-bit limitation, that were created to support the necessity. However, with the advent of IoT solutions, the necessity for addresses has increased, and according to the Ericsson company forecast in 2011, the number of connected things could reach 50 billion by 2020 (Nordrum, 2016). It is clear that the current capacity of IPv4 will not support this new demand, so companies should plan to migrate to the IPv6 protocol.

On this line, IPv6 addresses this gap, since it supports up to 340 deconstructions of addresses. It is composed of two parts (64 bits for network prefix and 64 bits for interface identifier), which will meet the need for IoT solutions in its fullness. In addition, IPv6 has better mobility and security compared to IPv4, since it is considered a mature and viable solution for the next generation of the Internet (Wu, 2013). **Figure 6** shows the difference between the IPv4 and IPv6 header.



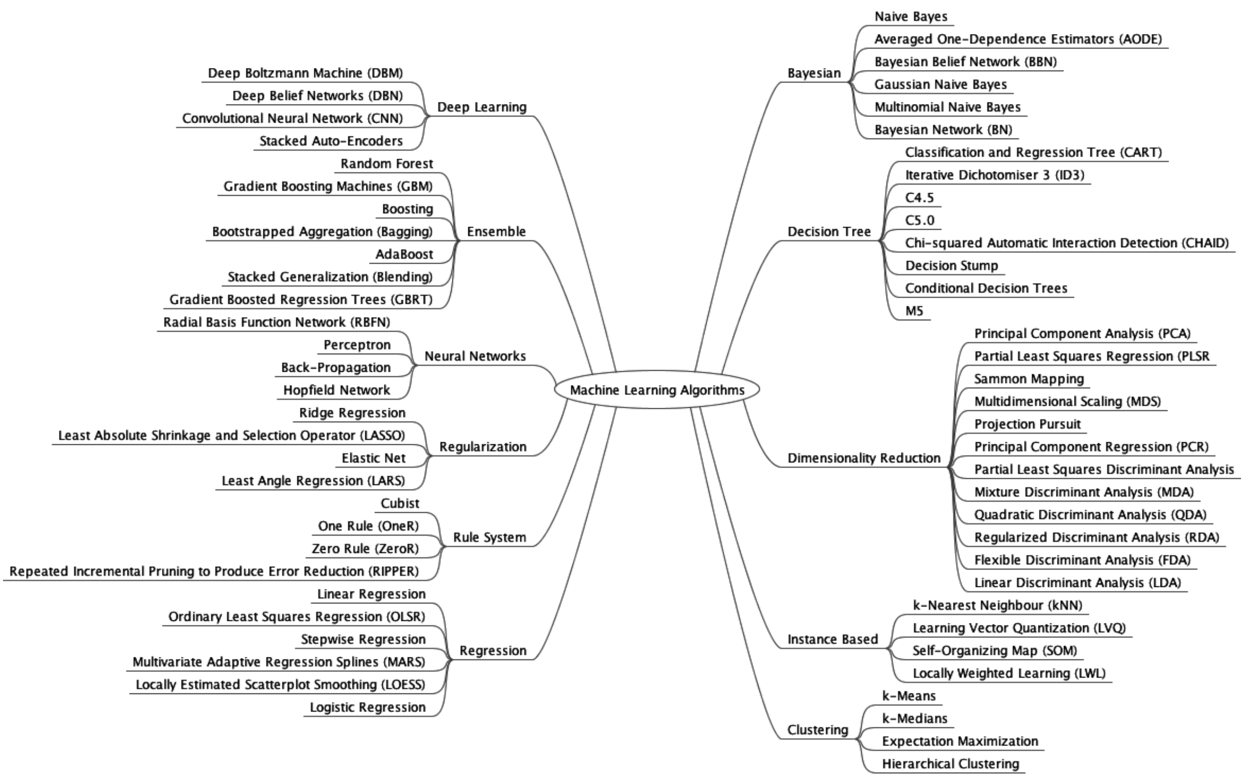
Source: (Wu, 2013).

Figure 6: Comparison between IPv4 and IPv6

2.7 Machine Learning

The first definition of machine learning was cited by Samuel (1959), defining it as the field of study that gives computers the ability to learn without being explicitly programmed. It was later redefined by Mitchell (1997), as techniques capable of improving his performance in a given task using previous experiences. According to Mitchell (1997), the algorithms for machine learning can be divided into four forms: supervised, unsupervised, semi supervised and reinforcement learning.

In supervised learning, data (inputs and outputs) are presented by means of a model, providing for each input the desired output, where the main objective is to learn a general rule in order to understand inputs and outputs. In unsupervised learning, no information is given to the algorithm, letting the algorithm itself understand the structure of the data. In the semi supervision algorithm, a training set is provided with some missing outputs. Reinforcement learning is about the interaction with a dynamic environment in which a specific goal is proposed, taking as a classic example the autonomous vehicles. The learning algorithms can be divided into predictive (classification and regression) and descriptive (grouping, summarization and association). The algorithms are used according to the purpose and the problem to be solved. This mind map, still not exhaustive, made by Jason Brownlee at Machine Learning Mastery highlights a number of diverse classes and subclasses of algorithms and approachs applied in Machine Learning, as **Figure 7** shows.



Source: (Data Science Central, 2016)

Figure 7: Machine learning algorithms

3. Literature Review: CNC Machines

This chapter presents the main concepts studied and analyzed about the types of programming of CNC Machines to carry out the necessary research for the project.

3.1 Concepts of CNC

Computer Numerical Control (CNC) is a control system that accepts a set of programmed instructions to control machines, mainly used in Lathe and Milling machines in machining processes. The system allows the simultaneous control of several axes, through a list of movements written in a specific code (G-codes). The CNC is an evolution from Numerical Control (NC), this technology was developed by the servomechanisms laboratory of MIT (Massachusetts Institute of Technology) in the USA. The development of NC technology can be categorized into various generations as listed below (Radhakrishnan, 2008):

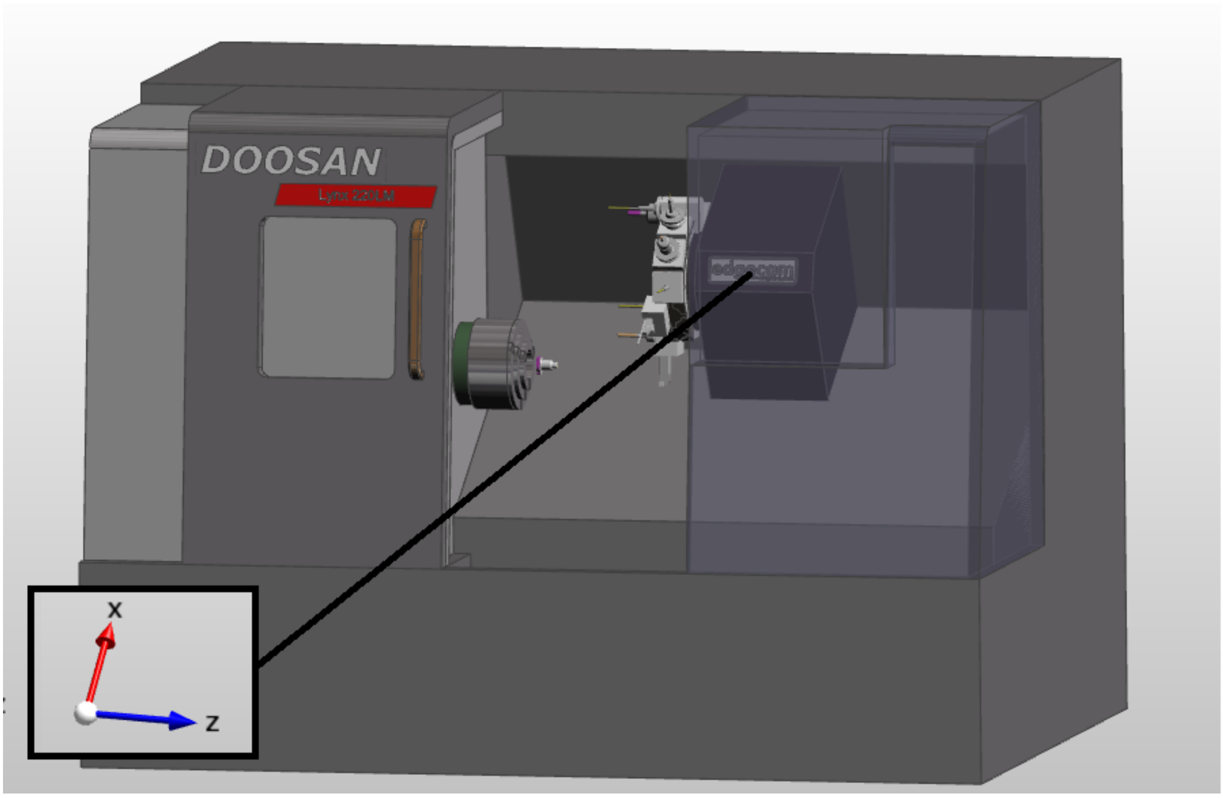
- **First generation:** The NC machines were built associating devices and vacuum tubes that consumed a lot of power and the storage capacity was poor.
- **Second generation:** The machines were created with transistors to use the PCB (Printed Circuit Boards). However, the size of the PCB was large and not satisfactory.
- **Third generation:** During the mid-60s, the concept of Integrated Circuit (IC) revolutionized the electronics world further. Thyristor Controlled DC drive became popular during this period. From the totally hardwired design, the design of NC machine become soft wired. At the same time, another development was the concept of evolution of direct numerical control technique by which several NC machines could be controlled by the a single host computer.
- **Fourth generation:** Near the end of 1970, microprocessors came to be used as a CPU of the computers, impacting on the design of CNC machine tools. Initially 8 or 16bit microprocessors were used. The system was improved and nowadays many CNC systems are based on 32 and 64 bit microprocessors as well.

3.2 Types of CNC Machines

When the CNC was created, the technology was adopted to fit on existing machines. Nowadays, the CNC technology is still being retrofitted to various machine tools, but there are many machines that were created for the specific purpose of being CNC machines (CNC 4 Everyone, 2018). For the sake of the study of the types of CNC machines for this dissertation, three main types of machining processes will be analyzed, which are: Lathe Machine, Milling Machine and 5 axis CNC Machine.

3.2.1 Lathe Machine

Normally, these machines are composed by two axis to program (X and Z) through G-codes, one Tool Turret and one Spindle. These machines rapidly rotate the material on a spindle. During the rotation of the spindle, the material is pressed against the tools to remove the materials and give shape as programmed. Lathes are mostly used to cut symmetrical objects such as spheres, cones and cylinders (Tag Team Manufacturing, 2017). **Figure 8** shows a Lathe Machine and the movement of the axis.

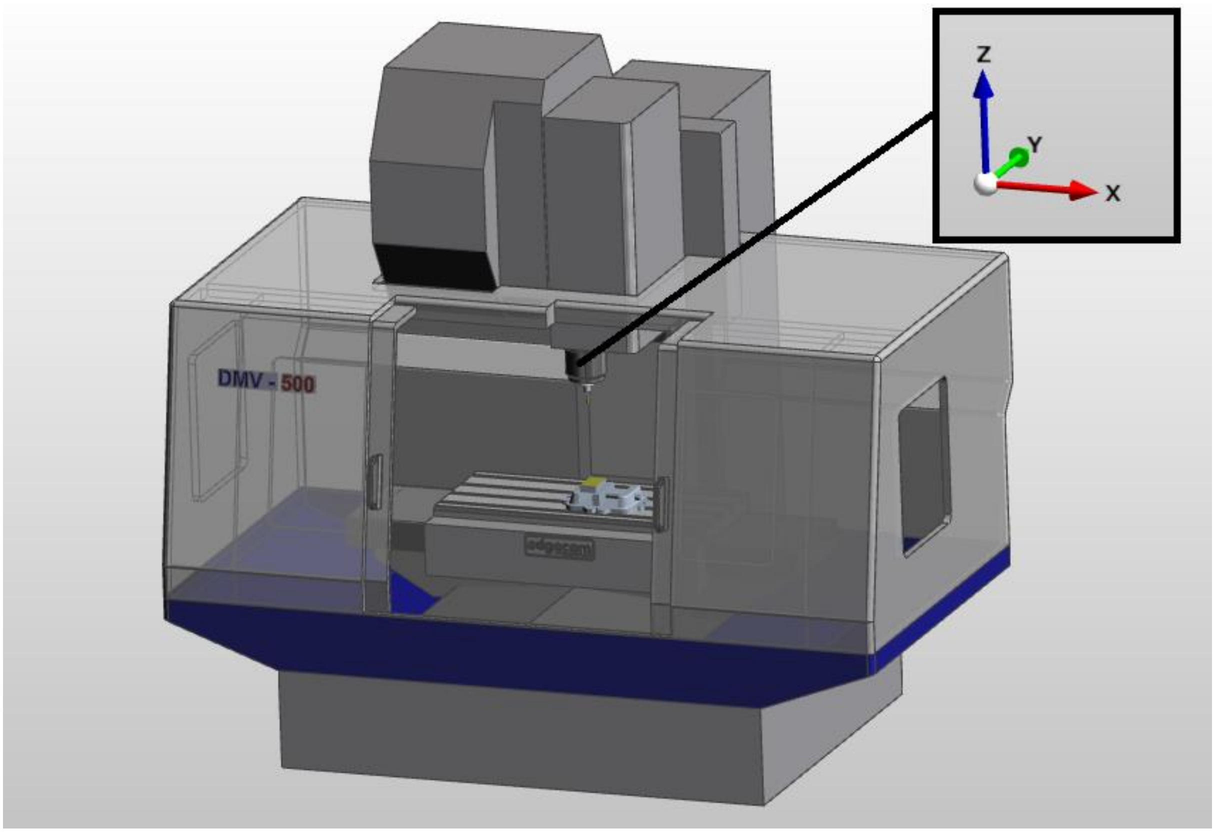


Source: Figure retrieved from EdgeCAM software and modified by the author.

Figure 8: The movement of the axis of Lathe Machine.

3.2.2 Milling Machine

The Milling machines usually are composed by three axis to program (X, Y and Z) through G-codes and one Table fix the material and sometimes, composed by one spindle to give the rotation when desired. Some of these machines are absolutely massive, have built in tool changers, auto-feed mechanisms for loading in material and various electrical sensors for safe monitored machining (CNC 4 Everyone, 2018). **Figure 9** shows a Milling Machine and the movement of the axis.

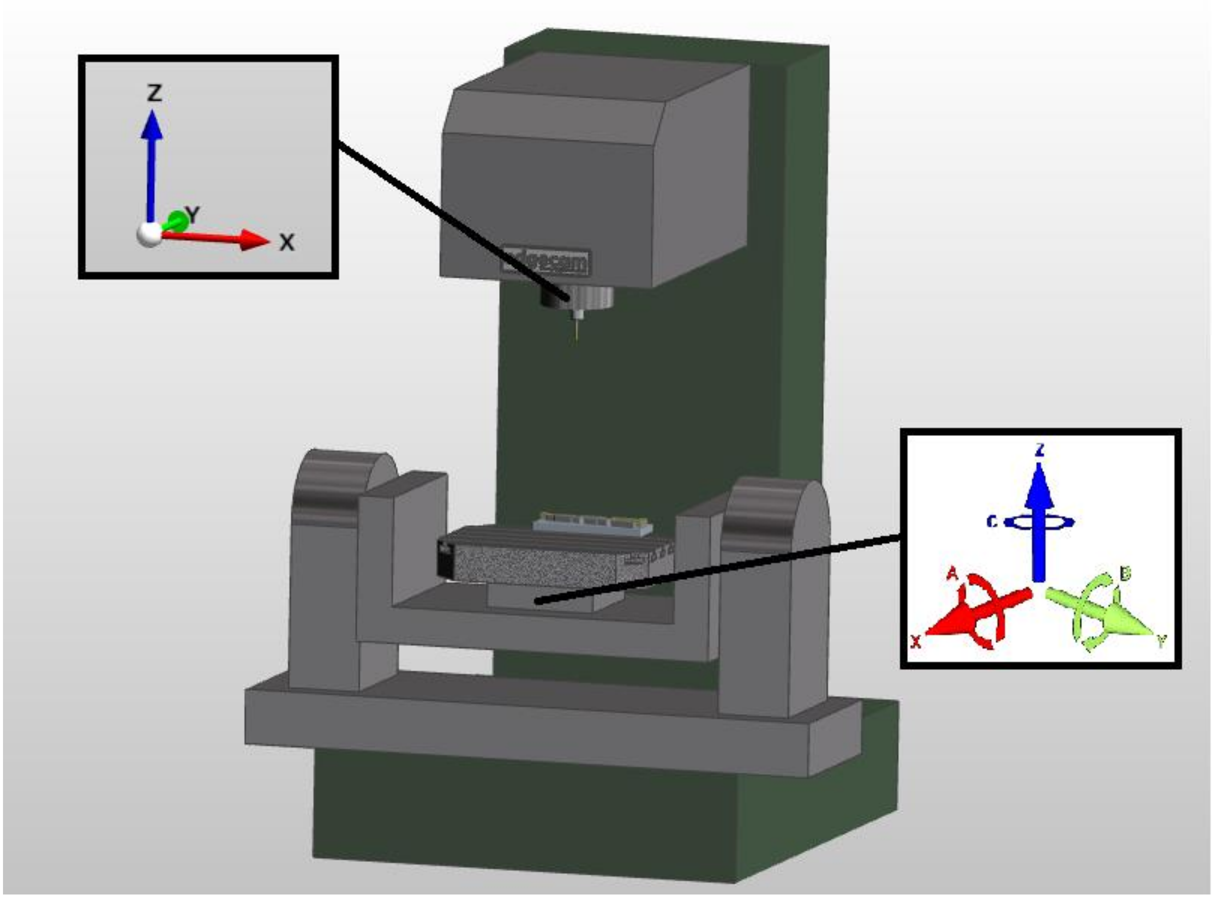


Source: Figure retrieved from EdgeCAM software and modified by the author.

Figure 9: The movement of the axis of Milling Machine.

3.2.3 5 axis CNC Machine

The 5 axis Machines as the name suggest is composed by five axis to program (X, Y and Z, as normal axis and A, B or C as rotary axis) through G-code programming. Normally, the axis X, Y and Z act on similar behavior of Milling Machine, the difference between them is because the 5 axis Machine has two more rotary axes. The rotary axes allow much more complex machining to produce parts that would be impractical to do on a normal CNC milling (CNC 4 Everyone, 2018). **Figure 10** shows a 5 axis CNC Machine and the movement of the axes.



Source: Figure retrieved from EdgeCAM software and modified by the author.

Figure 10: The movement of the axis on 5 axis CNC Machine.

3.3 CNC Programming

3.3.1 Requirements

Firstly, as Smid (2005) suggested to program a CNC machine, the programmer should always do before writing the program, is to evaluate the drawing in order to get a general idea about the part. Such an evaluation includes several observations that can be summed up:

- Drawing units and scale
- Dimensioning method
- Tolerances
- Material type, size, shape and condition
- Surface finish requirements
- Title block information

- Drawing revisions
- Bill of Materials (BOM) - if available
- Omissions and other errors

The CNC programming normally is based on G-codes. The G-codes is the language in which people tell computerized machine tools how to make something. These programs by G-code instructions are provided with a machine controller (industrial computer) that tells the motors where to move, how fast to move, and what path to follow (CMI, 2018). The CNC programming could be done manually by the CNC programmer or by CAM (Computer Aided Manufacturing). The most used G-codes are shown in **Table 1** followed by the M-codes on **Table 2** as used to program CNC machines in complement with G-codes.

Table 1: G-codes

Source: (CNC Cookbook, 2018).

Code	Category	Function	Notes
G00	Motion	Move in a straight line at rapids speed.	XYZ of endpoint
G01	Motion	Move in a straight line at last speed commanded by a (F)eedrate	XYZ of endpoint
G02	Motion	Clockwise circular arc at (F)eedrate	XYZ of endpoint IJK relative to center R for radius
G03	Motion	Counter-clockwise circular arc at (F)eedrate	XYZ of endpoint IJK relative to center R for radius
G04	Motion	Dwell: Stop for a specified time.	P for milliseconds X for seconds
G05	Motion	FADAL Non-Modal Rapids	
G09	Motion	Exact stop check	
G10	Compensation	Programmable parameter input	
G15	Coordinate	Turn Polar Coordinates OFF, return to Cartesian Coordinates	
G16	Coordinate	Turn Polar Coordinates ON	
G17	Coordinate	Select X-Y plane	
G18	Coordinate	Select X-Z plane	
G19	Coordinate	Select Y-Z plane	
G20	Coordinate	Program coordinates are inches	
G21	Coordinate	Program coordinates are mm	
G27	Motion	Reference point return check	
G28	Motion	Return to home position	
G29	Motion	Return from the reference position	

G30	Motion	Return to the 2nd, 3rd, and 4th reference point	
G32	Canned	Constant lead threading (like G01 synchronized with spindle)	
G40	Compensation	Tool cutter compensation off (radius comp.)	
G41	Compensation	Tool cutter compensation left (radius comp.)	
G42	Compensation	Tool cutter compensation right (radius comp.)	
G43	Compensation	Apply tool length compensation (plus)	
G44	Compensation	Apply tool length compensation (minus)	
G49	Compensation	Tool length compensation cancel	
G50	Compensation	Reset all scale factors to 1.0	
G51	Compensation	Turn on scale factors	
G52	Coordinate	Local workshift for all coordinate systems: add XYZ offsets	
G53	Coordinate	Machine coordinate system (cancel work offsets)	
G54	Coordinate	Work coordinate system (1st Workpiece)	
G55	Coordinate	Work coordinate system (2nd Workpiece)	
G56	Coordinate	Work coordinate system (3rd Workpiece)	
G57	Coordinate	Work coordinate system (4th Workpiece)	
G58	Coordinate	Work coordinate system (5th Workpiece)	
G59	Coordinate	Work coordinate system (6th Workpiece)	
G61	Other	Exact stop check mode	
G62	Other	Automatic corner override	
G63	Other	Tapping mode	
G64	Other	Best speed path	
G65	Other	Custom macro simple call	
G68	Coordinate	Coordinate System Rotation	
G69	Coordinate	Cancel Coordinate System Rotation	
G73	Canned	High speed drilling cycle (small retract)	
G74	Canned	Left hand tapping cycle	
G76	Canned	Fine boring cyle	
G80	Canned	Cancel canned cycle	
G81	Canned	Simple drilling cycle	
G82	Canned	Drilling cycle with dwell (counterboring)	
G83	Canned	Peck drilling cycle (full retract)	
G84	Canned	Tapping cycle	
G85	Canned	Boring canned cycle, no dwell, feed out	
G86	Canned	Boring canned cycle, spindle stop, rapid out	
G87	Canned	Back boring canned cycle	
G88	Canned	Boring canned cycle, spindle stop, manual out	
G89	Canned	Boring canned cycle, dwell, feed out	
G90	Coordinate	Absolute programming of XYZ (type B and C systems)	
G90.1	Coordinate	Absolute programming IJK (type B and C systems)	

G91	Coordinate	Incremental programming of XYZ (type B and C systems)	
G91.1	Coordinate	Incremental programming IJK (type B and C systems)	
G92	Coordinate	Offset coordinate system and save parameters	
G92.1	Coordinate	Cancel offset and zero parameters	
G92.2	Coordinate	Cancel offset and retain parameters	
G92.3	Coordinate	Offset coordinate system with saved parameters	
G94	Motion	Units per minute feed mode. Units in inches or mm.	
G95	Motion	Units per revolution feed mode. Units in inches or mm.	
G96	Motion	Constant surface speed	
G97	Motion	Cancel constant surface speed	
G98	Canned	Return to initial Z plane after canned cycle	
G99	Canned	Return to initial R plane after canned cycle	

Table 2: M-codes

Source: (CNC Cookbook, 2018).

Code	Category	Functions	Notes
M00	M-Code	Program Stop (non-optional)	
M01	M-Code	Optional Stop: Operator Selected to Enable	
M02	M-Code	End of Program	
M03	M-Code	Spindle ON (CW Rotation)	
M04	M-Code	Spindle ON (CCW Rotation)	
M05	M-Code	Spindle Stop	
M06	M-Code	Tool Change	
M07	M-Code	Mist Coolant ON	
M08	M-Code	Flood Coolant ON	
M09	M-Code	Coolant OFF	
M17	M-Code	FADAL subroutine return	
M29	M-Code	Rigid Tapping Mode on Fanuc Controls	
M30	M-Code	End of Program, Rewind and Reset Modes	
M97	M-Code	Haas-Style Subprogram Call	
M98	M-Code	Subprogram Call	
M99	M-Code	Return from Subprogram	

The CNC programming is not just based on G-codes or M-codes, there are other functions that are used to program as well. The most frequently codes to program a CNC machine is shown in **Table 3** (Smid, 2005).

Table 3: Most used codes on CNC Programming

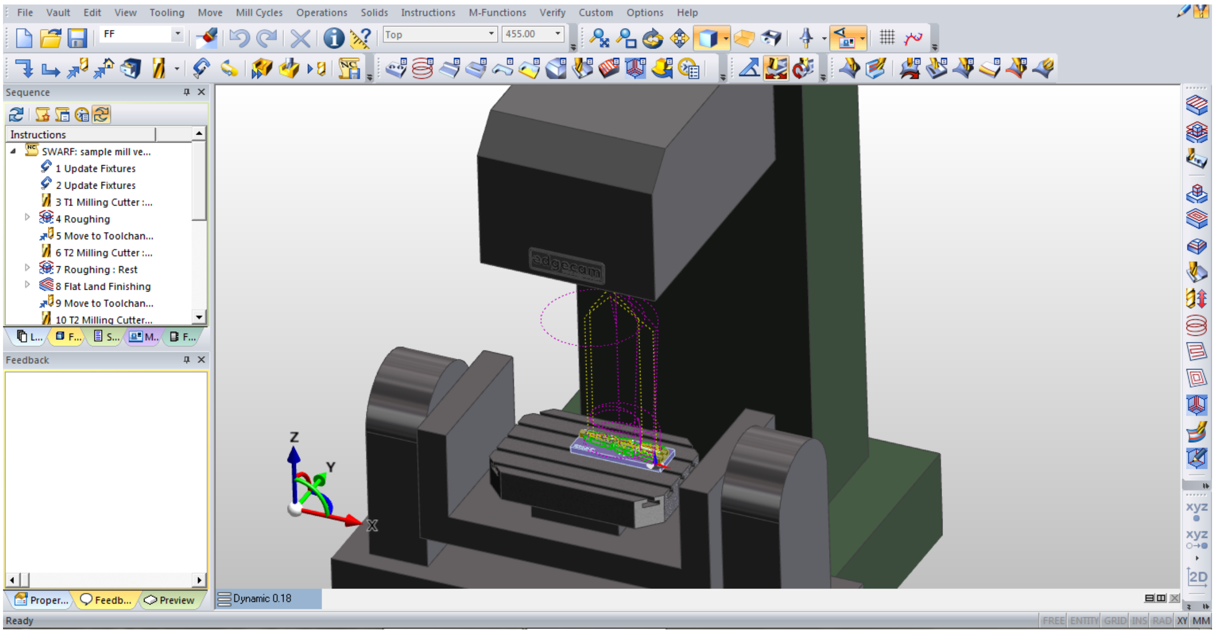
Source: (Smid, 2005).

Code	Description
A	Absolute or incremental position of A axis (rotational axis around X axis)
B	Absolute or incremental position of B axis (rotational axis around Y axis)
C	Absolute or incremental position of C axis (rotational axis around Z axis)
D	Defines diameter or radial offset used for cutter compensation. D is used for depth of cut on lathes. It is used for aperture selection and commands on photoplotters.
E	Precision feedrate for threading on lathes
F	Defines feed rate
G	Address for preparatory commands
H	Defines tool length offset.
I	Defines arc center in X axis for G02 or G03 arc commands. Also used as a parameter within some fixed cycles.
J	Defines arc center in Y axis for G02 or G03 arc commands. Also used as a parameter within some fixed cycles.
K	Defines arc center in Z axis for G02 or G03 arc commands. Also used as a parameter within some fixed cycles, equal to L address.
L	Fixed cycle loop count; Specification of what register to edit using G10
M	Miscellaneous function
N	Line (block) number in program; System parameter number to change using G10
O	Program name
P	Serves as parameter address for various G and M codes
Q	Peck increment in canned cycles
R	Defines size of arc radius, or defines retract height in milling canned cycles
S	Defines speed, either spindle speed or surface speed depending on mode
T	Tool selection
U	Incremental axis corresponding to X axis (typically only lathe group A controls)
V	Incremental axis corresponding to Y axis
W	Incremental axis corresponding to Z axis (typically only lathe group A controls)
X	Absolute or incremental position of X axis. Also defines dwell time on some machines (instead of "P" or "U").
Y	Absolute or incremental position of Y axis
Z	Absolute or incremental position of Z axis

3.3.2 CNC Programming by CAM (Computer Aided Manufacturing).

Using the codes suggested on tables before, it is possible to create manually a program for some desired work-piece using the right CNC Machine. Instead of it, for more complicated workpieces, there is another possibility to create a CNC program, which is by using a CAM software. The CAM systems work on the basis of mathematical models from the CAD (Computer Aided Design) system. Through these models the systems generate a toolpath file through the postprocessor (software that generates the machine-specific command program) on CAM. Through the CAM systems it is possible to transfer all coordinates, so the CNC Machines carry out the machining of the part (John, 1984).

The CAM software permits a simulation on a computer before a real execution on CNC Machine, but the program parameters are totally dependent from the CNC programmer. **Figure 11** shows the workspace of EdgeCAM as a CAM software and then an example of the program generated by the postprocessor.



Source: Figure retrieved from EdgeCAM software.

Figure 11: Workspace of EdgeCAM as a CAM software

An example of the CNC program generated by EdgeCAM´s postprocessor for Lathe Machine:

%_N_CEN0000_MPF

;$PATH=/_N_MPF_DIR

;(PROGRAMMER: ACENDINO ALVES)

```
N10 G0 G54 X200 Z200 T0 M5
N20 T301 ;(EXT./PCLNL-2525-M12/R.4)
N30 G96 S150 M3
N40 G92 S1200
N50 G0 X-3.864 Z0.946 M8
N60 G1 X-0.4 Z-0.054 F0.2
N70 X14.32 Z-4.303
N80 G3 X14.712 Z-4.594 I-0.2 K-0.346
N90 G1 X25.372 Z-42.517
N100 X28.468 Z-45.198 F.2
N110 G3 X28.574 Z-45.398 I-0.346 K-0.2
N120 G1 Z-48.676
N130 X30.838 Z-47.545
N140 G0 Z10
N150 G0 G54 X200 Z200 T0 M9
N160 M30
%
```

4. Literature Review: Machining tools for CNC machine

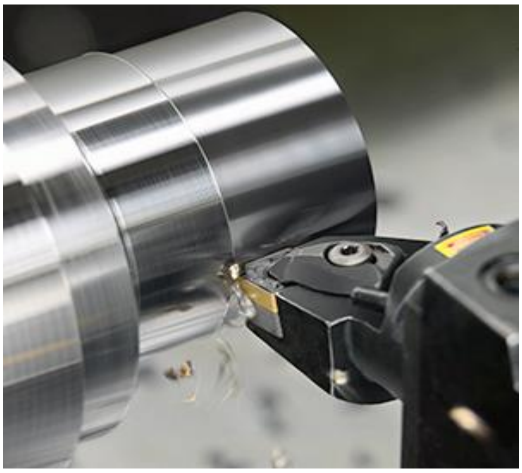
4.1 Process Machining for CNC

The operations on process machining for CNC are chosen by analyzing of the technical drawings to execute the workpiece (Vedric, 2013). From the sample drawing, even a casual look will identify the types of operations required to machine the part (Smid, 2005). Actually, there are numerous operation of CNC machine, but basically the most used are three:

- Turning
- Milling
- Drilling

4.1.1 Turning

Normally turning operation is executed on Lathe Machines, where the Spindle fixes the material through the Chuck, rotating against the tool and transforming on the workpiece as desired. Turning is a process that generates cylindrical and rounded forms with a single point tool. The workpiece rotates against the tool. On metal cutting, Turning is the most common process, is a highly optimized process. Thereby, it requires various factors in the turning application. Turning can split in numerous simple applications on CNC machines (longitudinal turning, facing or profiling) for selection of tool types, cutting data and programming (Sandvik Coromant, 2017). **Figure 12** shows an example of a turning operation.



Source: (Sandvik Coromant, 2017)

Figure 12: Tuning operation on CNC Machine

4.1.2 Milling

The Milling operation different from the Turning operation. The tool rotates against the workpiece removing material to transform the shape as desired. Milling is the machining process of using rotary cutters to remove material (Sandvik Coromant, 2017). This process is one of the most used on CNC machines, because it covers a wide variety of different operations and machines. **Figure 13** shows an example of milling operation.

Source: (Sandvik Coromant, 2017)

Figure 13: Milling operation of CNC Machine

4.1.3 Drilling

Drilling as the name suggest is a cutting process that uses a drill to cut a hole of circular cross-section in solid materials. Drilling is another common process of CNC machines. In Lathe Machines the workpiece rotates against the drill. Concerning to Milling machines and 5 axis CNC machines, the drill is pressed against the workpiece and rotated removing the material (Sandvik Coromant, 2017). **Figure 14** shows an example of Drilling operation.

Source: (Doc Player, 2018)

Figure 14: Drilling operation of CNC Machine

4.2 CNC Tools

4.2.1 Requirements

The tools used on CNC Machines are chosen in accord with the processes to be executed. For each process operation there are many types of tools, but basically they are built on the same principle, remove the material through the forces applied from the workpiece or tool to transform the raw material into a shape desired as a final workpiece (Sandvik Coromant, 2017). The machining tools are usually composed of a tool body and a cutting edge for removal of material as shown in **Figure 15**. The cutting edge is usually made through the inserts to remove exchanges when damaged.

Source: Figure retrieved from Sandvik Coromant and modified by the author.

Figure 15: Simple parts of CNC Tool.

4.2.2 CNC tools with cyber-physical technology

Actually, the tools with cyber-physical technology is a term totally new on machining. As the manufacturing on automotive industry has employed connectivity, remote monitoring and intelligent use of data for years, the company Sandvik, one of the most important companies on development of CNC tools cutting edge, recently introduced a new tool with cyber-physical technology, the *CoroPlus®.* According to Sandvik Coromant (2017) this new tool is a combination of sensors, connectivity, algorithms, the cloud, data analysis and connection with Internet of Things (IoT) that can help improves the manufacturing process, cut costs and reduce waste. The ever-increasing digitalization of manufacturing opens new opportunities to increase the productivity and effectiveness (Botkina, Hedlind, Olsson, Henser, & Lundholm, 2018).

For this new technology on tools, the International Organization for Standardization (ISO), developed the ISO 13399. For Botkina et al., (2018), the ISO 13399 is today the international technical standard for information to exchange information between various software servicing cutting tools and holders, and between tool manufacturers and suppliers. This standard was developed to help the use, manipulation on exchange information in cutting tool data and manufacturing. The **Figure 16** shows the picture of the *CoroPlus®* as the tool with cyber-physical technology.

Source: (Sandvik Coromant, 2017)

Figure 16: CoroPlus®, the tool with cyber-physical technology.

5. EXPLORING HOW THE CNC TOOL DEVELOPED WITH CPS WORKS ON THE CNC

As a new tool with cyber-physical technology has emerged in the CNC machining area, the technology with combination of sensors, algorithms, the cloud, data analysis, and connectivity with Internet of Things (IoT), it came up an opportunity to know how this tool works on CNC machines to analyze the benefits for future productions.

This research could help a better understanding of how this new technology works and can help for future productions. According to Botkina et al., (2018), ever increasing digitalization of manufacturing opens new opportunities to improve productivity and effectiveness.

This new tool disposes a cyber-physical technology. Within the scope of manufacture, Cyber-physical Systems (CPS) correspond to the physical and virtual systems in an integrated network that brings together physical resources and processes (Gorecky, 2014). In these networks it circulates multiple information from different sources that are monitored and synchronized between the factory and cyberspace (Lee et al., 2015). For this new technology on tools, the International Organization for Standardization (ISO), developed the ISO 13399.

5.1 ISO 13399 – Cutting tool data representation and exchange

Actually ISO 13399 is the international technical standard for information exchange between various software servicing cutting tools and holders, and between tool manufacturers and suppliers (Botkina et al., 2018). The ISO 13399 has been developed with contributions from Sandvik Coromant, the Royal Institute of Technology in Stockholm, Kennametal Inc., and Ferroday Ltd.

According to ISO 13399-2:2014 (2014), the ISO 13399 is divided into several parts:

- Part 1: Overview, fundamental principles and general information model
- Part 2: Reference dictionary for cutting items
- Part 3: Reference dictionary for tool items
- Part 4: Reference dictionary for adaptive items
- Part 5: Reference dictionary for accessory and auxiliary items
- Part 50 Reference dictionary for reference systems and common concepts
- Part 60: Reference dictionary for connection systems
- Part 100: Definitions, principles and methods for reference dictionaries

- Part 150: Usage guidelines
- Part 301: Concept for the design of 3D models based on properties according to ISO/TS 13399-3: Modelling of thread-cutting taps, thread-forming taps and thread-cutting dies
- Part 302: Concept for the design of 3D models based on properties according to ISO/TS 13399-3: Modelling of solid drills and countersinking tools

This document makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving, regarding cutting tools

5.2 CNC Tool System

According Sandvik Coromant (2017) the tool with cyber-physical system is a combination of sensors, connectivity, algorithms, the cloud, data analysis and with connectivity with Internet of Things (IoT). This topic will help for a better understanding of how these systems work on the tool. The tools with CPS have two main subjects, the CPS and IoT, related to the concept of Industry 4.0, which is our main interest in this dissertation.

5.2.1 Cyber-Phisycal System (CPS) on CNC Tools

Leitão, Colombo, & Karnouskos, (2016) argue that the Cyber-Physical Systems (CPS) is an emerging approach that focus on the integration of computational applications with physical devices and is designed as a network of interactive physical and cybernetic elements. The CPS controls and monitors real-world physical infrastructures and have a high impact on industrial automation.

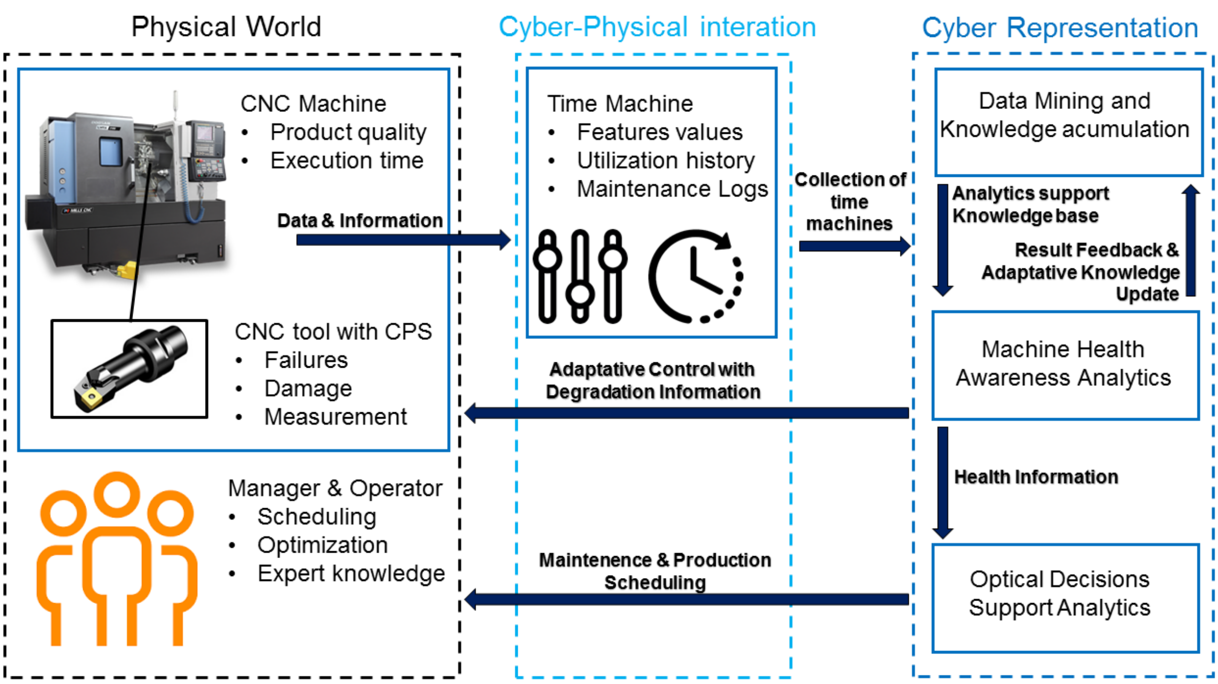
On CNC machine tool the manufacturing resources are the parts of the physical system which are required in order to perform machining tasks. Manufacturing resources are the tools and materials, as cutting tools, machine tool, fixture and parts, and also the machining environment, like vibration and temperature. The CNC machine tool makes a specific work task with given manufacturing resources. Through the operation status data, the resulting work, quality and productivity of CNC machine can be expressed by the characteristic parameters in the work process.

For Chen et al., (2015), the result, in the CPS model of a CNC machine tool work process, includes a model input, which consists of two parts, the work task and manufacturing resources, while the output is the corresponding operation status data when the machine tool performs a task.

The CPS model of a CNC machine tool work process can be defined in association with the work task, manufacturing resources and operation in the Cyber System (CS) in parallel with Physical System (PS).

In CNC tools, the Cyber-Physical System (CPS) takes the application data through connected software and hardware, with sensor-equipped tools they can adjust, control and monitor machining performance in real time as shown on **Figure 17.**

The CNC machine can be controlled via accurate on site data dashboards, through the cloud and via integration with the user's software and machine environment. The tool with CPS, connects into existing software, offering two-way connectivity and accurate data quality (Sandvik Coromant, 2018). The **Figure 18** gives a better understanding as an example.



Source: Figure retrieved from Sandvik Coromant, Doosan, Google images and modified by the author.

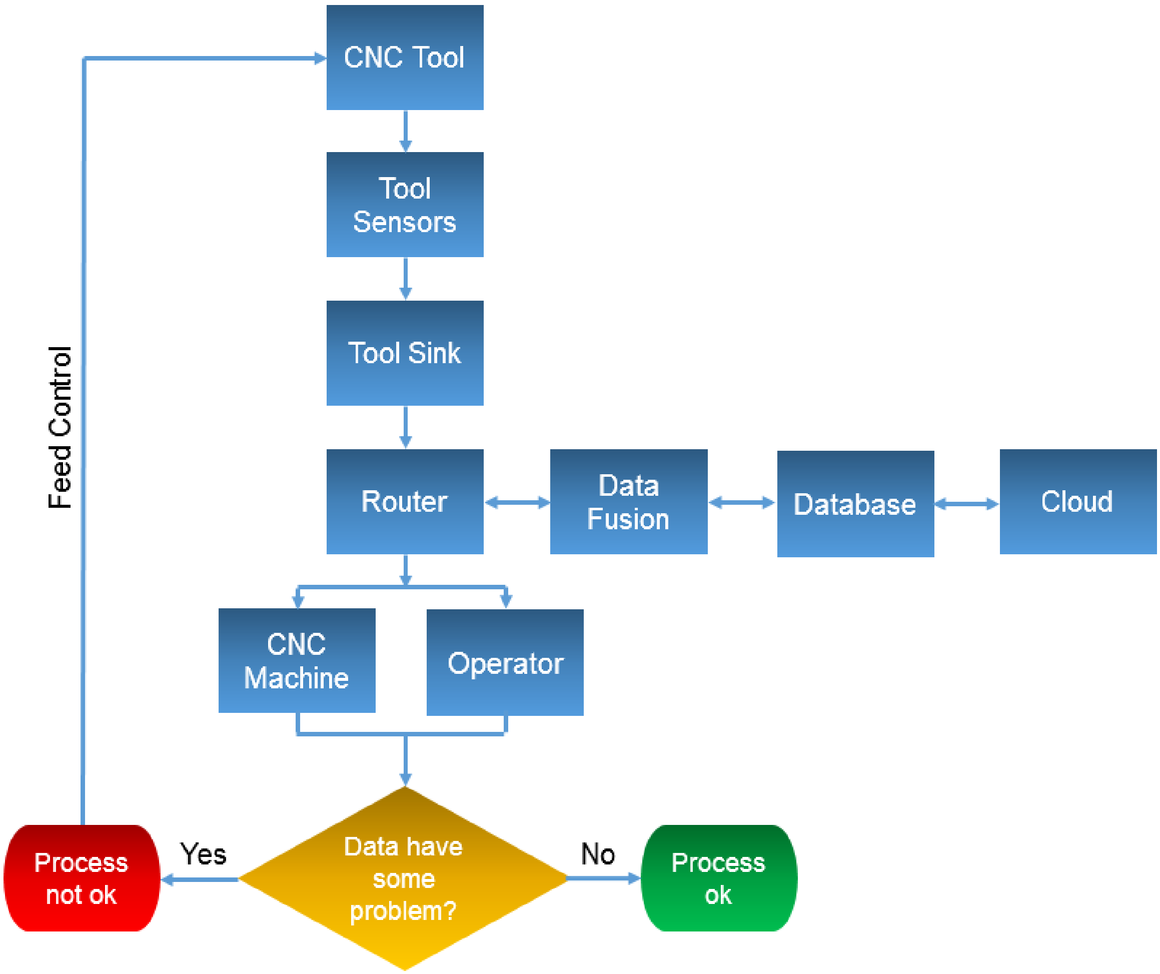
Figure 17: Cyber- Physical System on CNC communication.

Source: Figure retrieved from Sandvik Coromant, Doosan, Google images and modified by the author.

Figure 18: Cyber- Physical System interaction on CNC machine, tool and operator in real time.

In these networks, multiple information circulates from different sources that is monitored and synchronized between the factory and cyberspace (Lee et al., 2015).

The information captured by the tool is informed to the CNC machine and Manager/Operator through CPS connected software and hardware, where the data could be managed and monitored to get a better precision and quality on production in real time. The tool gives the information in real time execution and, if some problem happens, the tool can detect the collision and a reliable solution can help avoid or minimize machine tool and workpiece damage. The operator can monitor the machining process in real-time and interact with the machine tool when the tool detects the overload forces. These can help the operator on time execution, where other actions can be programmed if some problem occurs. The flow process of the data from the tool to a CNC machine and Operator can be seen on the flowchart in **Figure 19**.



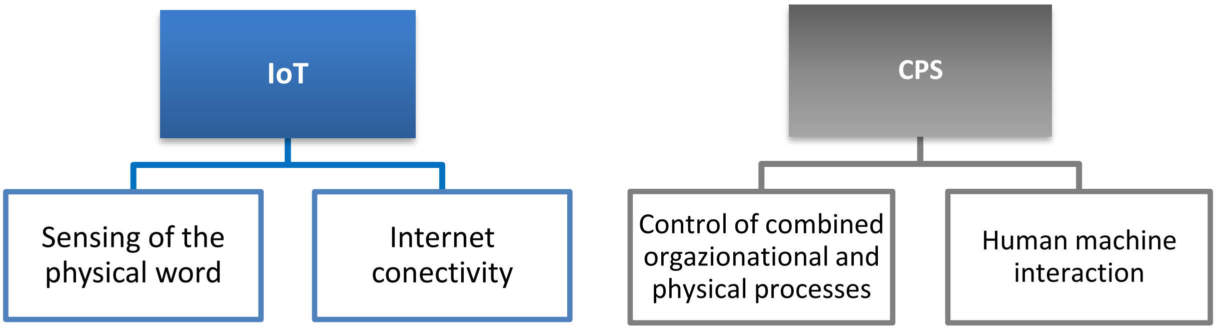
Source: Elaborated by the author

Figure 19: Flow data on process from CNC tool to CNC machine and Operator.

5.2.2 Internet of Things (IoT) on CNC Tools

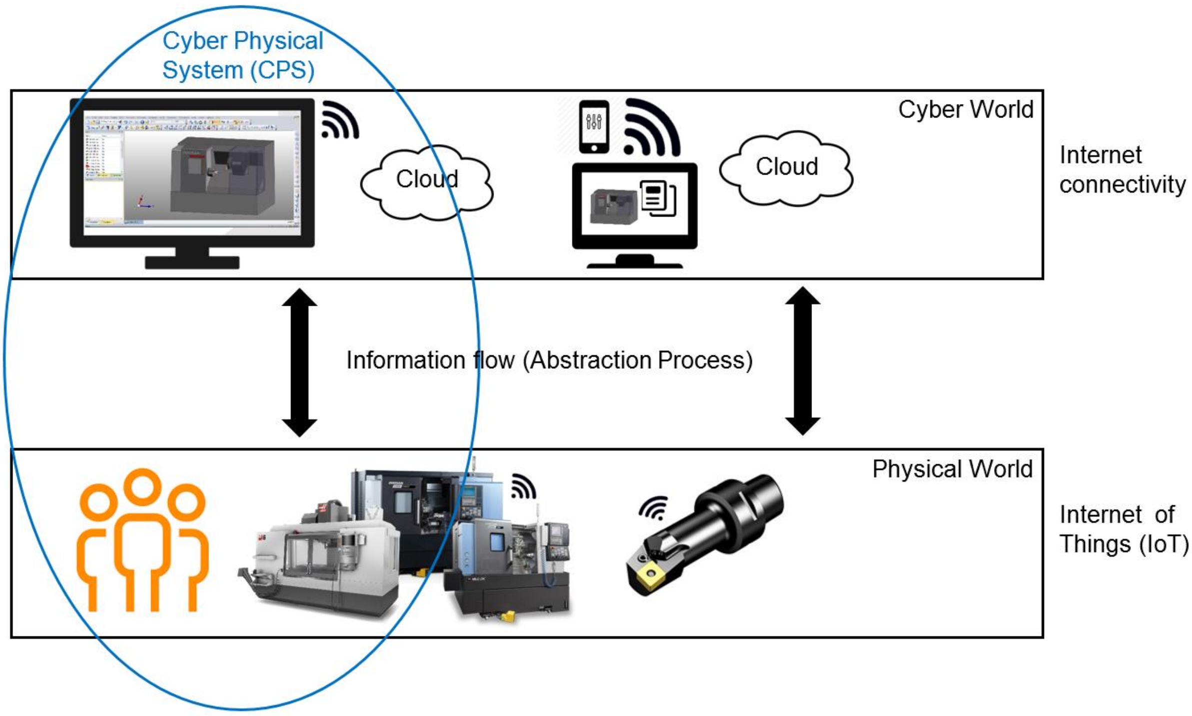
The Internet of Things is nothing more than an extension of the current Internet, which provides to the objects nowadays, but with computing and communication capabilities, the possibility to connect to the Internet. CNC tools connected with Internet of Things (IoT) could monitor the machining performance and make decisions about how to optimize the processes based on accurate information. Cloud based analytics and local systems enable to use all the data collected on machining operations.

The Internet of Things (IoT) refers to a network of interconnected objects that are addressable exclusively and are based on standard communication protocols. The design of Cyber-Physical Systems and the implementation of their applications need to rely on IoT enabled architecture and protocols, manage and process large datasets, and support complex processes to manage and control those systems at different scales. The large scale nature of IoT based CPS can be effectively and efficiently supported by Cloud Computing infrastructures and platforms, which can provide flexible computing power, resource virtualization and high-capacity storage for data flows and ensure security, protection and privacy. **Figure 20** shows the main difference between the CPS and IoT, and **Figure 21** shows the Cyber Physical System works with IoT on CNC tools. The IoT is a key domain in which data streams are generated, and the volume of this data is expected to increase (Jang, Jung, & Park, 2018).



Source: Elaborated by the author

Figure 20: Internet of Things (IoT) versus Cyber- Physical System (CPS).



Source: Figure retrieved from Sandvik Coromant, Doosan, Haas, Google images and modified by the author.

Figure 21: Architecture of CPS with IoT on CNC tool.

The Internet of Things (IoT) is responsible to sensing of the physical world, where it is responsible to network interconnected objects that are addressable exclusively, like the sensors on CNC tool. So, they take the information flow of the abstraction process through sensors and transfer it to the Internet with world connectivity where it is transferred to the Cloud Computing infrastructures and platforms, which can provide flexible computing power, resource virtualization and high-capacity storage for data flows and ensure security, protection and privacy.

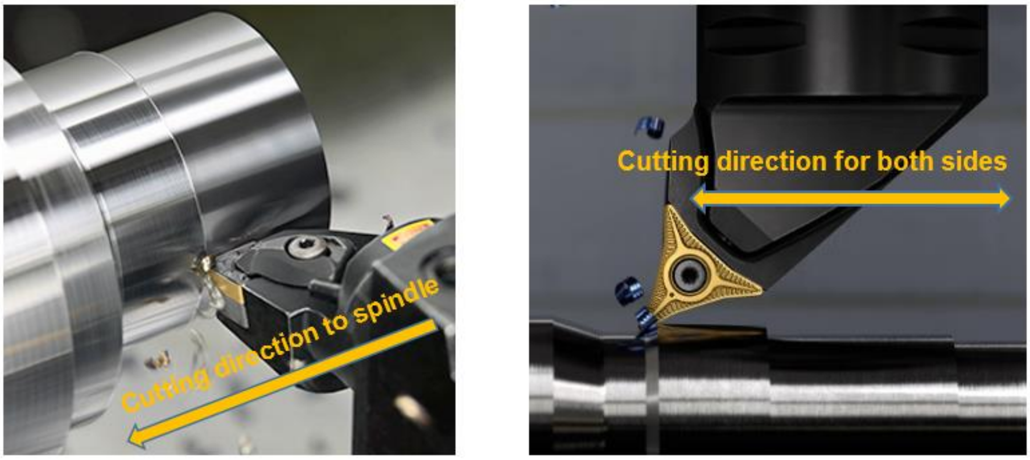
5.3 Tool Functions

The tool with CPS provides tree mains functions that could help the production integrated with software on CNC machines. They are:

- ToolPath code generators
- In-cut monitoring
- Process monitoring

5.3.1 ToolPath code generators

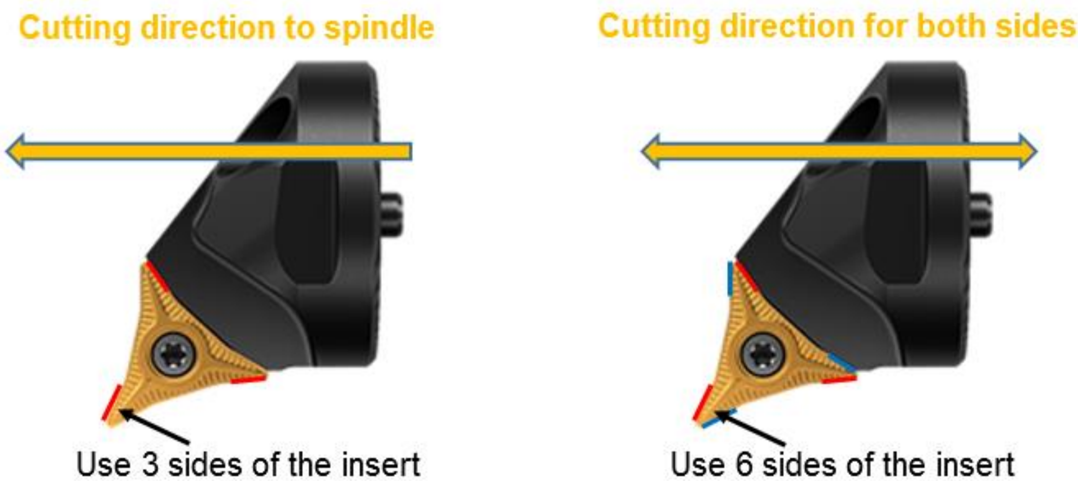
The ToolPath code generators on CNC machine, permit create optimal tool paths in the process executed on machining. The CNC tool from Sandvik Coromant provides a software to supply the programming codes (G-codes), and some technique's application different from traditional process (Sandvik Coromant, 2018). On turning process methodology as cited in **Chapter 4**, this system enables to execute the turning in all directions working much more efficiently and productively compared to traditional turning. **Figure 22** shows the difference directions between the traditional turning operations with traditional tool and the actual propose by Sandvik with ToolPath on turning operation.



Source: Figure retrieved from Sandvik Coromant and modified by the author.

Figure 22: Directions of the traditional turning operations and the tool with ToolPath.

The programming using this software permits you to create the program with the cutting in all directions, increasing the production and reducing the time. The software allows the programming with G-codes, following the constant cutting direction, differently from actual programs where the program cycles are created with just one cutting direction returning without cutting the material. The lost time on execution when the tool returns without cutting the material is reduced, and the ToolPath allows the cutting directions for both sides, allowing constant cut. But this program is just possible if the right tool is chosen to execute this process, the tool must have the cutting edge in both directions. This method helps prevent waste of inserts because the insert's edge will be used in almost all sides, and not just one side as the traditional process tuning does. **Figure 23** shows the comparison between the possibilities to use the insert´s sides.

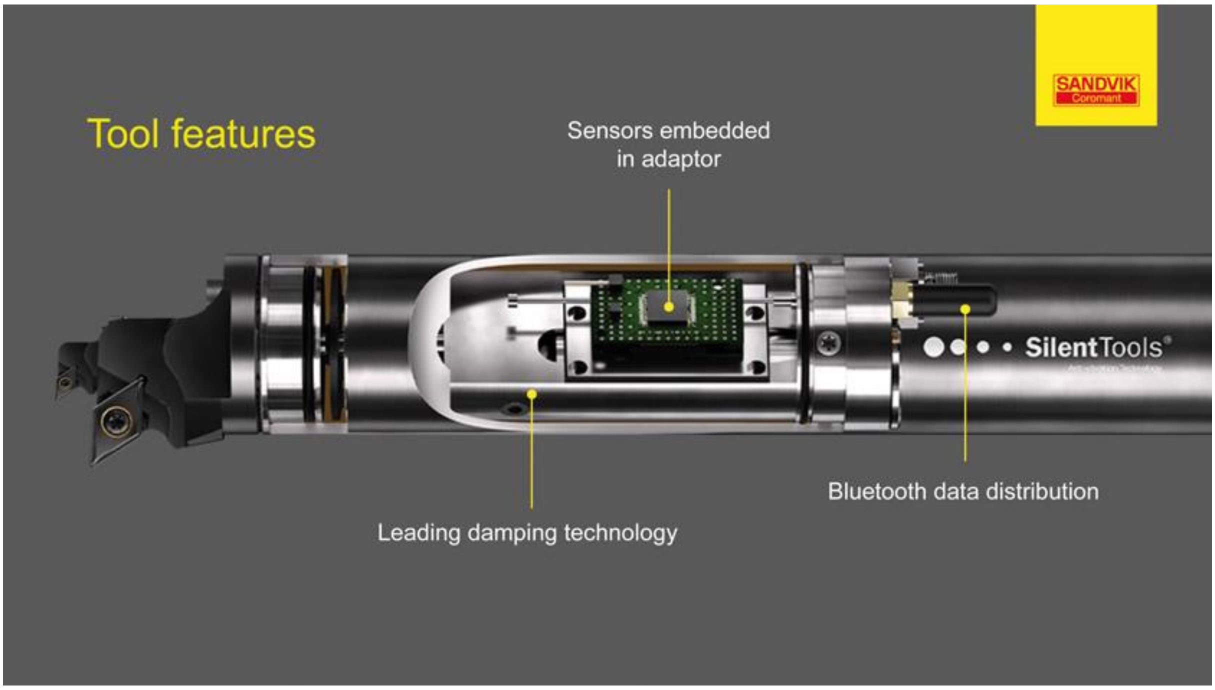


Source: Figure retrieved from Sandvik Coromant and modified by the author.

Figure 23: Comparison of the possibilities to use the inserts sides.

5.3.2 In-cut monitoring

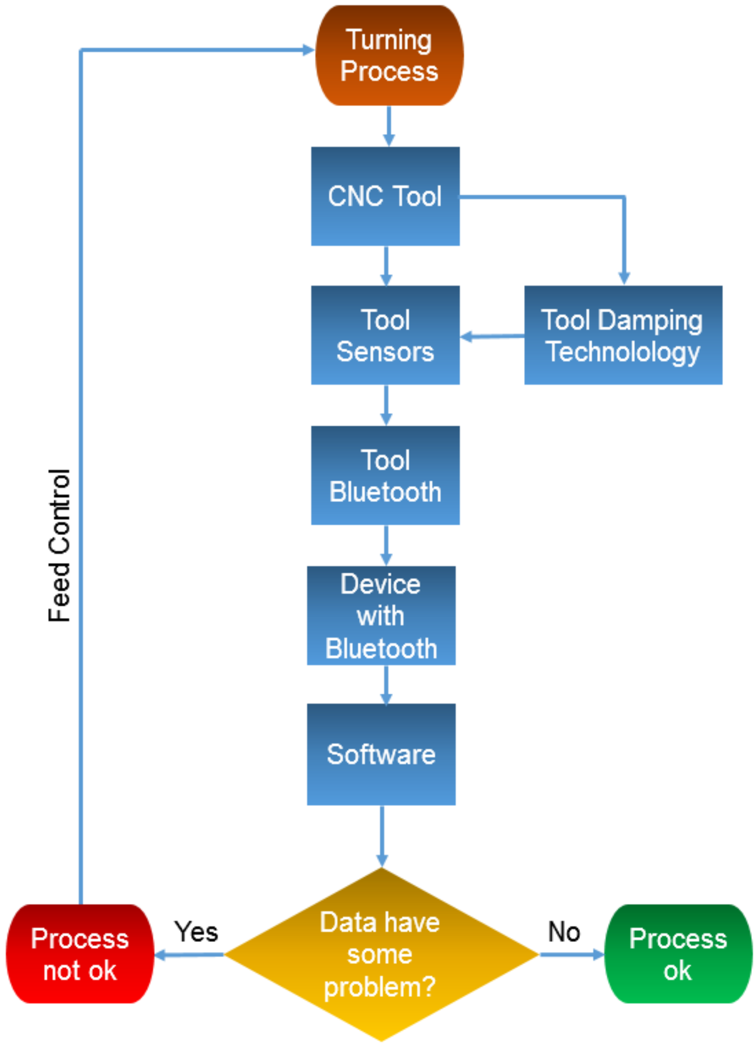
The technology In-cut monitoring on CNC tools, includes a mechanism in the tool that allows the monitoring of the cutting in real time. The adapters connected to the tool help the process control problems with long tools that could vibrate on internals turning processes and increase the opportunities to process learning and optimization. The information in the execution of production in real time is transmitted by the tool, giving the data about what is going on inside the machine and process, which enables the operator to take the right action to change or improve the process (Sandvik Coromant, 2018). This technology provides a software that could monitor the behavior of the tool in the process execution. On the tool developed by Sandvik, whose name is Silent Tool, there is a technology that tries to inhibit the frequency of vibration and the sensor takes the information on process execution to send to the software through Bluetooth technology. **Figure 24** shows the internal system technology of the Silent Tool.



Source: (Sandvik Coromant, 2018).

Figure 24: Internal system technology of the Silent Tool

The software in combination with the Silent tool provides information about what is happening on process execution. This combination could help the problems with long turning tool because the tools tries to inhibit the frequency vibration through the internal system in leading damping technology. Basically the flow process of tool´s data is shown in **Figure 25**, presenting the information taken by the tool and transferred to the software. The sensors took the information about the vibration, surface roughness, in-cut and temperature. These combinations of information help the operator take the right decision.



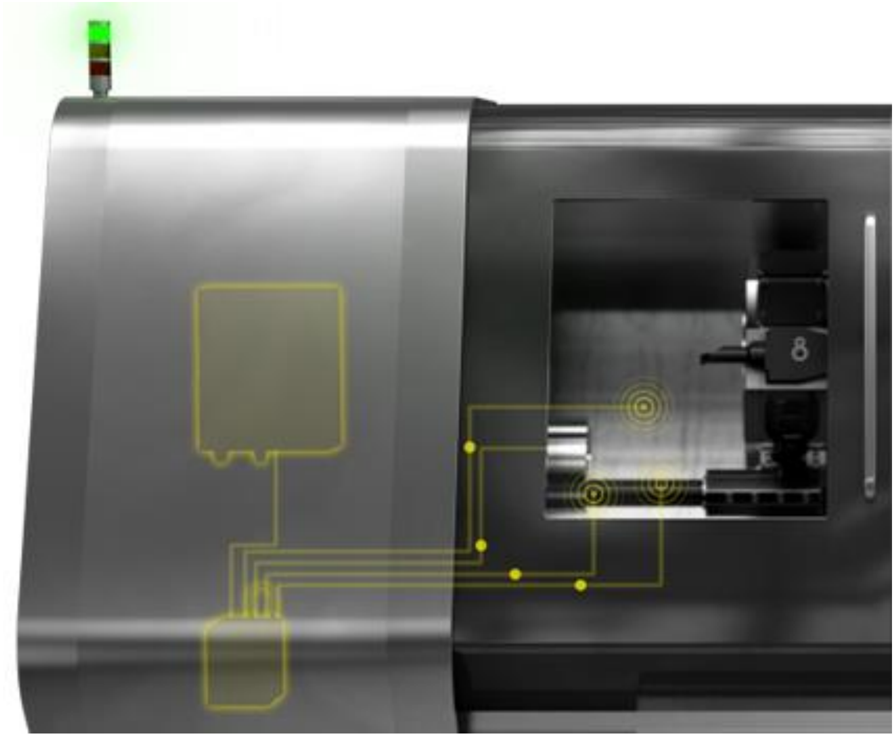
Source: Elaborated by the author

Figure 25: Flow of data from turning process to the software.

This flowchart shows the data captured by the tool for turning process until it arrives on the software, when the information indicates some problem with the process presented by the software, which allows the operator to make the right changes in the process execution and consequently have a better quality of execution.

5.3.3 Process monitoring

The CNC tool with CPS helps the control of process machining on CNC machine through the implementation of software and hardware, providing the communication about what is happening on the machine system (Sandvik Coromant, 2018). The CNC tool in communication with the software installed on CNC machine enables to detect the collision and report the machine condition that could help improve the productivity and knows the actual situation of the CNC machine. **Figure 26** shows the system interaction if some problem occurs.



Source: (Sandvik Coromant, 2018).

Figure 26: System interaction between tool and machine if some problem occurs.

This tool function could minimize the damage if some problem happens, like, for instance, if a wrong programming did the machine or workpiece collide against the tool. For Sandvik Coromant, (2018), the software and hardware installed on the machine is connected to Programmable Logic Controller (PLC) that can detect the collision and react within five milliseconds to stop the machine. This tool could also inspect the health condition of the CNC machine, making the analysis about the tool’s spindle, slide, and bearings, which could help to know if the machine needs some maintenance or not. If some problem is detected on machine system it could help the operator/manager do predictive maintenance.

5.4 Advantages in production

The CNC tool with Cyber Physical System brings some advantages in production that could benefit the current practices in machining area. For Zhang, Jiang, Cheng, Xu, & Ma, (2015) the implementation of the CPS generates a thorough knowledge of the monitored system that could bring a lot of benefits to the production and the proper presentation of the acquired knowledge to expert users correct the decision to be taken. Thereby, the CNC tool with CPS brings some advantages in production, like:

- Virtual production control
- Virtual interaction between Human, Machine and tool
- Data saved on Cloud
- Reduction of inserts waste
- Collision detector
- Machine health inspector

5.4.1 Virtual production control

One of the main advantages using the CNC with CPS is the possibility of the production controlled virtually. The connections between the real world and the cyber world helps to take the right decision if some problem occurs on the production in real time.

Example: If on the turning process, the tool is vibrating, is above temperature friction, or the insert is damaged. The tool in communication with software and machine directly informs what is happening to the operator/manager and helps to take the right decision to solve the problem.

5.4.2 Virtual interaction between human, machine and tool

Differently to the subtopic above, this advantage is the interaction between human, machine and tool working comprehensibly. The benefit is if some problem occurs during the process execution on the machine or tool, the software gives the information about what happened to the operator, and the operator could make the changes without stopping the machine.

Example: During the turning process execution of one workpiece, if the speed is lower or higher than advised, the operator could increase or decrease the speed of the next process execution without stopping the operation.

5.4.3 Data saved on cloud

One of the most obvious advantages of using the CNC tool with CPS, the benefit to save the information on cloud, is the possibility to save the actual information on the process to use on future productions with similar characteristics.

Example: On the turning process, the parameters used to programming the speed, velocity and feed, could be used for similar process executions on future productions. The right behavior analysis collected by the tool, could be used for others process.

5.4.4 Reduction of inserts wastes

The right shape of the tool with CPS working with the provided software as cited in **Chapter 5,** help to get a constant cut execution of the process (saving time) and using the cutting direction for both sides, possibly by the use of insert in both sides, and consequently increase the use of the insert by 50%.

Example: The traditional CNC turning process has the cutting direction just to one side, returning to the initial position without cut (lost time). The CNC tool with CPS with the right shape, and connected to the software permits constant cutting using both sides of the insert.

5.4.5 Collision detector

The Collision detector function provided on process monitoring by the CNC tool is a really important advantage and could help in the reduction of the damage to the workpiece, the tool and the machine. The capacity to react instantly when some problem happens could represent large cost savings.

Example: If the CNC program has some not correct parameter, and the machine is colliding against the workpiece, the reacted information taken by the CNC tool could stop the machine and decrease the damage.

5.4.6 Machine Health inspector

This function could help with the internal systems information about what is happening to CNC machines. If some CNC machine component has some problem, the sensor from the tool could detect it and inform the operator through the software and hardware.

Example: If the spindle is not working correctly, the technology combination takes the information and sends it to the operator or manager, and then, they could provide and program a predictive maintenance.

5.5 Impact on Human Labor

Since the beginning of robotics and automated machines, one of the principal issues was the implication it has on human labor. In manufacturing processes with the implementation of robotics and automated machines, the process was established in which automatable action sequences were performed by machines and non-automatable tasks continued to be performed by humans (Decker, Fischer, & Ott, 2017).

The substitution of human labor is focused on achieving an increase in efficiency through labor cost savings.

As Decker et al., (2017) argue, assembly lines were developed in which automated operations could be optimally coordinated and the non-automatable action could be executed by human works, calling the residual activities where one part of the function on the automated line could be executed by humans as upstream or downstream tasks.

On CNC machines a similar situation has happened. The CNC was a development from NC and NC the development of mechanical machines. The operations were manually executed on mechanical machines and when the process was automated by the NC, the operator continued working doing residual activities. Thereby, the process started to work more efficiently and faster, because the routine services were automatically done. Later, with CNC development, microprocessors came to use as a CPU of the computers to help the machine work more efficiently. The human labor was not too much affect with the transformation from NC to CNC, because the human kept doing the part non-automated of the functions, changing the workpiece on the machine, preparing the right tool, and changing the parameters manually on the machine if some problem occurred.

The relationship between human and machine changes over time: both are substitutes in early phases of technology development and become complements as the technology advances (Decker et al., 2017).

Strictly speaking, as Decker et al., (2017), argue, the question of whether human labor is substituted by service robots or automated machines can only be answered in a non-speculative way, if the benefit of human labor output is identical to the benefit provided by a robot, presuming that in a capitalist society the cost–benefit analysis then made is always the sum of individual business decisions and interesting.

One can analyze this question by talking about the effects this new CNC tool developed with the Cyber Physical System, which brought some benefits, as cited on **Sub-Chapter 5.4,** and strictly checking the human labor changes brought about by the implementation of this tool.

Concerning the communication between human and the application of this CNC tool with CPS, the changes in human labor are:

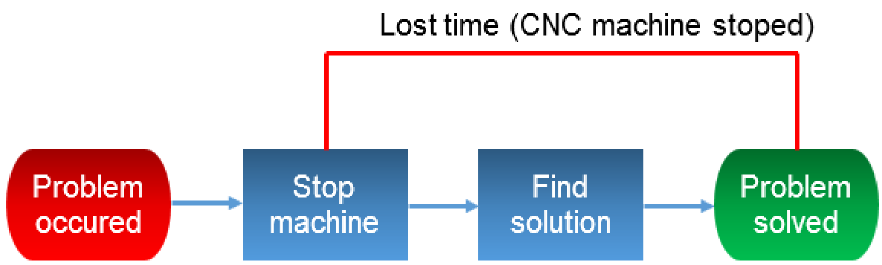
- The cutting parameters will not be only depend on human knowledge, if a similar process has been executed before.
- Check the tool if the insert is damaged.
- Decrease of tool preparation on CNC machines.
- Decrease the verification of autonomous maintenance by the operator

5.5.1 The cutting parameters will not be only depend on human knowledge, if a similar process has been executed before.

As cited before one of the advantages is the interaction between human, machine and tool working comprehensively and the possibility that the data is saved on a cloud. The problems of process execution will be not only dependent on operator/manager knowledge to solve it. As a similar process has been executed before, this information could be saved in the cloud and be used for other process operations, helping with the best choice to be done. The difference between the scenarios using the CNC tool with CPS could be seen bellow:

- Scenario with traditional CNC tool:

If some problem occurs during the process execution, the operator needs to stop the machine and verify the problems and find a solution to solve it (lost time). **Figure 27** shows the flowchart of the process to be taken if some problem happens.

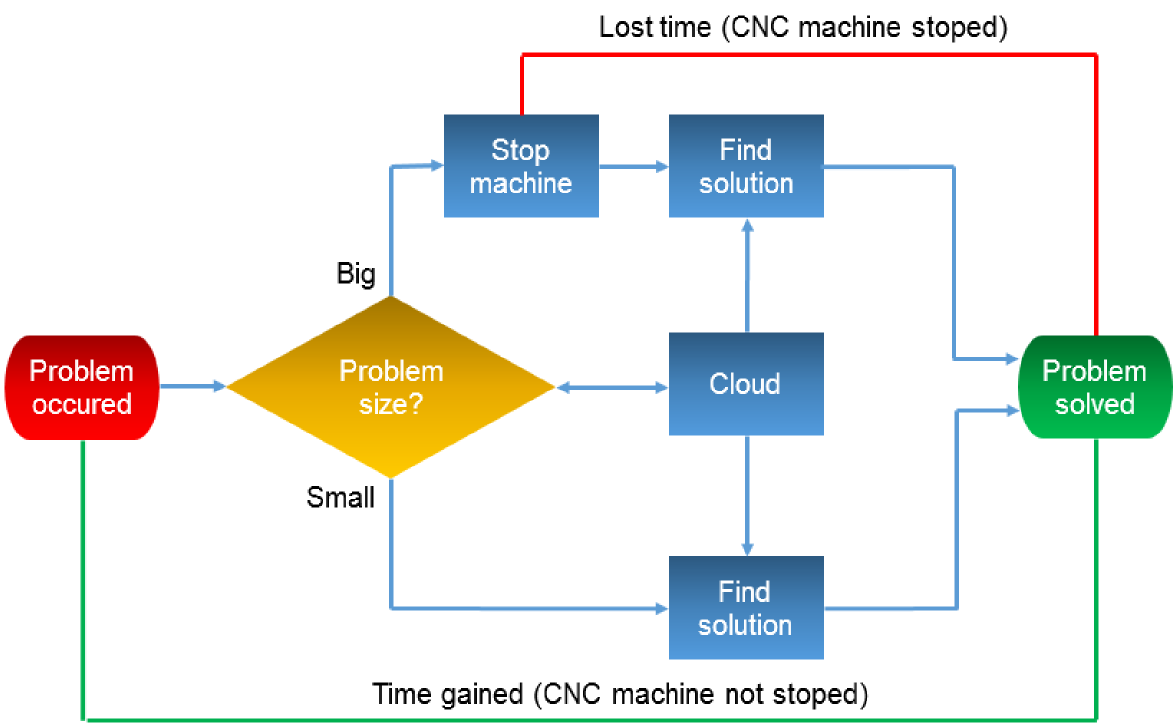


Source: Elaborated by the author

Figure 27: Process to do if some problem occurs with the traditional CNC tool.

- Scenario with CNC tool with CPS:

If some problem occurs during the process execution, the operator could analyze the problem, and its significance, through the information given by the tool virtually. This information is saved on cloud, and could help with the right decision to be taken. Thereby, the operator can check if it needs to stop the CNC machine or do not stop. Sometimes, the problems could be solved on the process execution without stopping the machine. **Figure 28** shows the process if some problem occurs with the CNC tool with CPS.



Source: Elaborated by the author

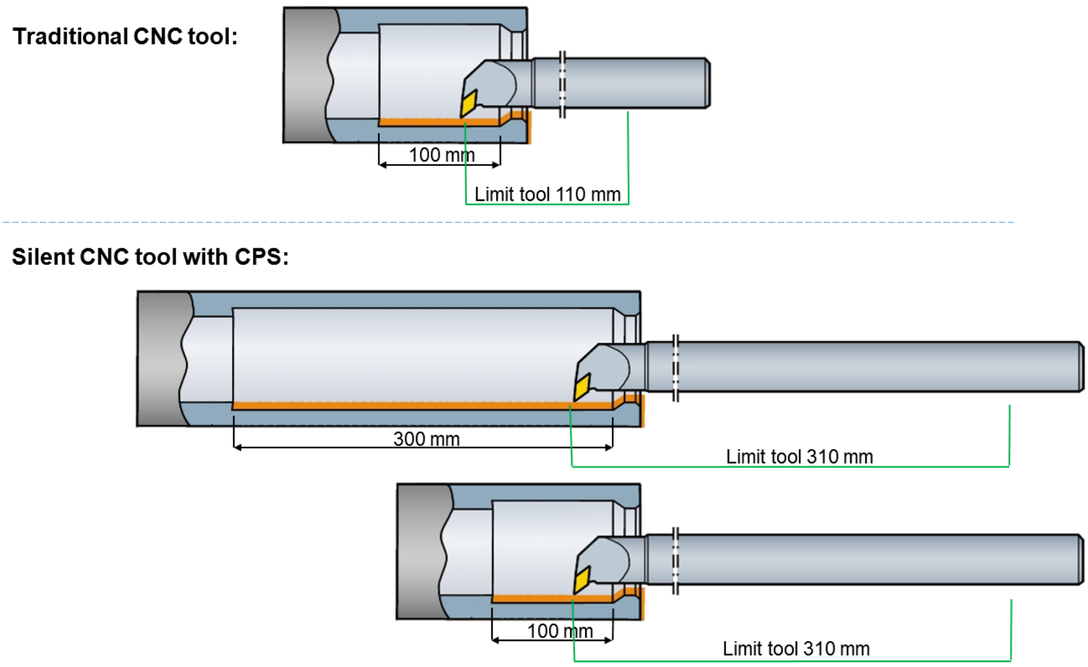
Figure 28: Process if some problem occurs with the CNC tool with CPS.

5.5.2 Check the tool if the insert is damaged.

Normally on process executed with the traditional CNC tools on CNC machines, the operator needs to be alert if the cutting tool (insert) is working properly, if he thinks there are some problem trough the workpiece roughness or some noise. He could stop the machine to verify the problem. Instead of it, using the CNC tool with CPS, the information about the damage and workpiece roughness is given by the tool transporting to the software where the operator could check if the insert need to be changed or not without stopping the machine.

5.5.3 Decrease of tool preparation on CNC machines.

The preparation for CNC machines is one of the main worries on the machining area, because the preparation requires a time to be planned, prepared and then executed. Thereby, inside this situation, the right CNC tool needs to be chosen by the human labor to change to the next operation. There are many types of CNC tools to be used according to the operation to be executed (turning, milling, drilling, etc.). Especially on internal turning process, the CNC tool with leading damping technology as cited in **sub-chapter 5.3** could help to decrease the tool changes on CNC machines because the limited length of the tool is chosen according to the depth of the workpiece (if it is a short deep turning, a short length tool is chosen. If it is a "long deep turning", a long tool is chosen). The "long deep turning" operation could be a problem on internal operations, because of the vibration. That is why most of the process do not leave a long tool assembled with a CNC machine to use in all internal operations. Instead of it, the tool with leading damping technology (Silent tool) could inhibit the frequency of vibration and this long tool could be used to execute all operations, short deep operations and long deep operations, consequently reducing the changes of tools for CNC preparation and so, reduce the human labor tasks. **Figure 29** shows how the Silent tool could be used to execute the short and long operations with internal processes.



Source: Figure retrieved from Sandvik and altered by the author.

Figure 29: Limit of the tool to execute the process.

5.5.4 Decrease the verification of autonomous maintenance by the operator of the CNC machine

Generally, on CNC machines the autonomous maintenance is done by the operator or other workers on the manufacturing area. This maintenance could be from just a change of the oil or the change of some CNC component. The health machine inspector cited in **sub-chapter 5.4**, could verify the behavior inside the machine. This technology system, could help give the information about the machine directly to the maintenance sector and consequently does not need the autonomous maintenance executed by the operator.

6. PROPOSAL FOR FUTURE APPLICATIONS

In the last couple of years the industrial automation is increasing and accommodating the emerging technologies. The emergent approach Cyber Physical System (CPS) which focuses on the integration of computational applications with physical devices, controlling the interaction between the physical real world and the cyber world is having a high impact in industrial automation (Leitão et al., 2016).

Having in mind the possibility to explore how the CNC tools developed with Cyber Physical System work on the CNC, it came up the opportunity to give a proposal on how this technology could work in future applications on CNC machines. Through the analysis and the knowledge acquired, two technologies could be implemented that might help the CNC machining area on future applications:

- Tool measurement
- Communication with the social network

The proposal constitute novel approaches which were idealized, developed and matured by the author, and constitute original content that contributes to new knowledge on the topic. Two new additional proposals will be made in the following chapters, which also contribute to advance knowledge in the respective domains.

6.1 Tool measurement

In order to ensure the precision machining measurements on CNC machine, numerous inspections and measurements are done on the CNC process, where most of the time are done by the operator when the CNC machines are stopped. These measurements and inspections normally are executed using the manual metrology instruments (micrometer, caliper, surface roughness gauge, etc.) as shown in **Figure 30**, which consequently consumes production time and increases the operation cost.

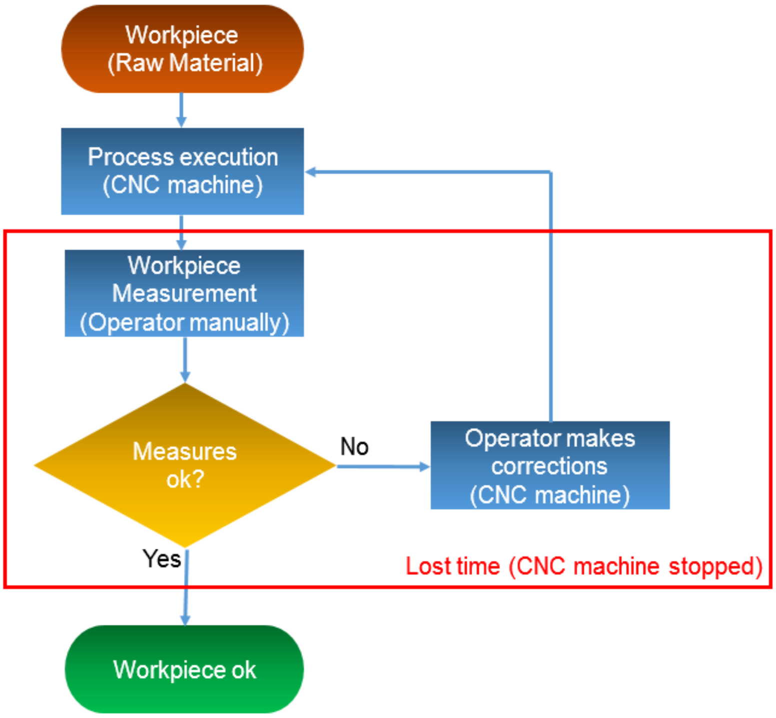
Source: Figures retrieved from Mitutoyo.

Figure 30: Metrology instruments.

The proposal to "Tool Measurement" on CNC machines, is basically to use the CNC tool with the Cyber Physical System, and provide it with the ability to exchange information about the measurement on process execution through the sensors. As such, the workpiece could be measured during the process execution, and when the process is done the workpiece would be already measured, do not losing time with the stopped machine. In essence, this proposal has the following implications, which will be discussed by contrasting the actual and the future scenery concerning the measurement issue.

- The actual scenario of measurement on CNC machines:

As mentioned before, the actual process measurement on CNC machines is normally executed by the operator when the machine is idle. This happens because the CNC machine does not have the capacity to make the correction automatically, and so the operator needs to do the measurement in the workpiece and CNC machine with the metrology instruments, and he needs to make the corrections to compensate the incorrect measures. This process happens until the workpiece conforms to the technical drawings used. The flow measurement process is shown in **Figure 31**.

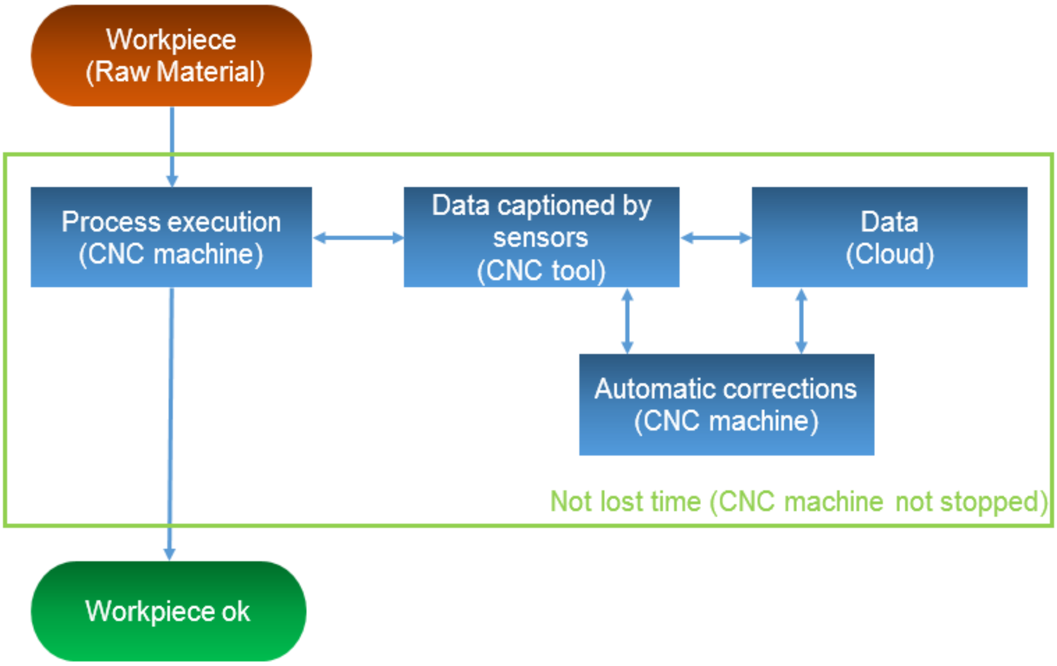


Source: Elaborated by the author

Figure 31: Actual measurement process on CNC machines.

- The Future scenario to measurement on CNC machines:

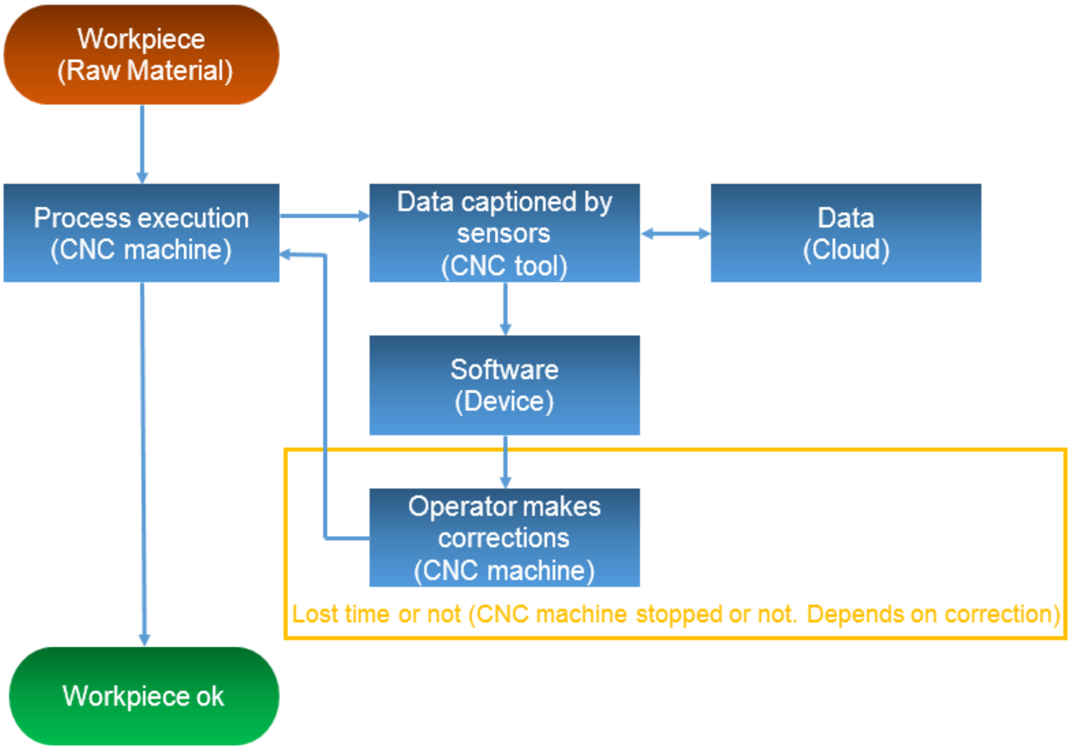
For the future scenario, two proposals for future applications in the measurement process with CNC machines will be presented. Firstly the ideal one, is the CNC tool with Cyber Physical System which gives the information about the measurement on process execution through the sensors, and the software and hardware connected with the CNC machine have a capacity to make the automatic corrections during the process execution in real time. In other words, through the information collected by the sensors, the tool and CNC machine could work together if the CNC machine has the capacity to receive the information from the cloud and make the corrections automatically. So, the lost time on the measurement process in CNC machine would not exist. **Figure 32** shows the idea how this process measurement could work.



Source: Elaborated by the author

Figure 32: First proposal to measurement process on CNC machines.

The second proposal to measurement on CNC machines addresses the situation in which the software and hardware installed on CNC machine do not have the capacity to make the automatic corrections in real time. The corrections, in that case, could be done by the operator, in real time or when the machine is stopped, depending on the correction. The difference relative to the actual scenario is that the operator will have the information transferred by the tool in his device to the software, where he could see on the software the corrections to be done, and does not have to do the measurements with the metrology instruments that consume time to be executed on process measurement. The operator will be responsible just to do the necessary information for corrections to the CNC machine, where the machine could execute the process to make the modifications. Actually, this process to give the information to CNC machine by the operator is a relatively quick part of the process when the machine is stopped. The idea of this second proposal is shown in **Figure 33.**



Source: Elaborated by the author

Figure 33: Second proposal to measurement process on CNC machines.

6.2 Communication with social network

Relative to the proposal of the communication with a social network and considering the possibility of CNC tool with Cyber Physical System in communication with IoT (Internet of Things), the idea is to give to the tool the ability to communicate with social networks (Facebook, Twitter or LinkedIn), where they could create some groups to discuss about the problem in real time or post as a discussion.

For instance, if the CNC machine is machining a special material who is in development and the parameters are not defined for process execution yet, the company could use the information collected by the tool and share a discussion on groups on social network, increasing the chance to solve the problem through the knowledge of the people on the network, or could change the information with others partners companies who share similar productions. The option to create an internal group or an open group on social networks, will be the choice of the company. This possibility of the connection with social networks could also help with advertising and marketing, showing the actual processes for the company, about solutions on real time and the process execution. This proposal could help in production control when, for instance, each process has been executed, the manager/owner could receive the information through the social network about what is going on. **Figure 34** shows the architecture how this process could work.

Source: Figure retrieved from Doosan, Haas, Sandvik, google images and altered by the author.

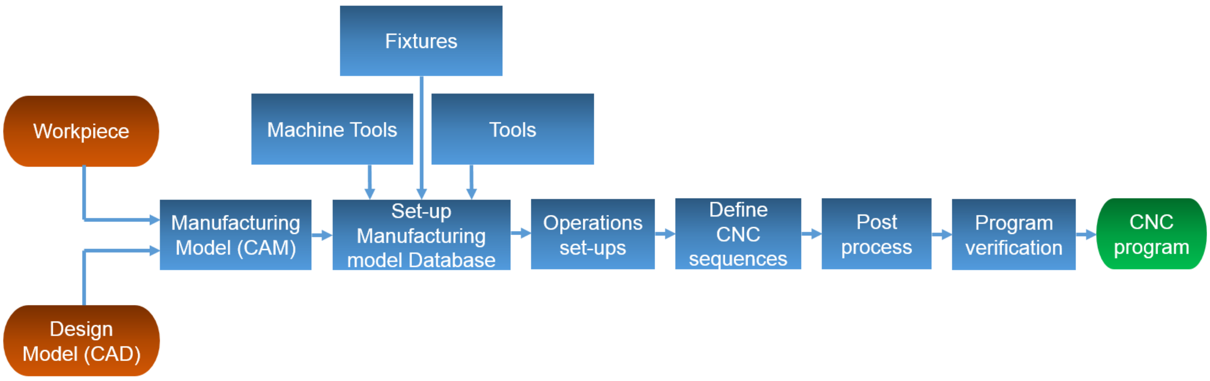
Figure 34: Architecture of the process with interaction with social network.

7. STUDYING HOW A CAM SOFTWARE WORKS IN COMMUNICATION BETWEEN TOOLS WITH CYBER PHYSICAL SYSTEM AND A CNC MACHINE

The new tool with Cyber Physical System that has been recently developed in the CNC machining area, and the exploration about this technology has been done on the topic before, raises the opportunity to know how this tool could work integrated with a CAM software and CNC machine. The main aim of this chapter is to study how a CAM software works in communication between the tool with CPS and a CNC machine, presenting the CAM possibilities of connection and effects.

The introduction of computer graphics allows to create the virtual workpieces on the computer, handle and study them. The universal application of computer aided brings substantial benefits to the manufacturing area. CAM (Computer Aided Manufacturing) is a software associated with functions in manufacturing engineering, used to process planning and CNC programming (Dubovska, Jambor, & Majerik, 2014).

Radhakrishnan (2008), show in their book the steps of the process to create a CNC program using a CAM software package, which can be seen in **Figure 35**. They explain step by step the procedure from the Computer Aided Design (CAD) file for the creation of a CNC program.



Source: (Radhakrishnan, 2008) and altered by the author.

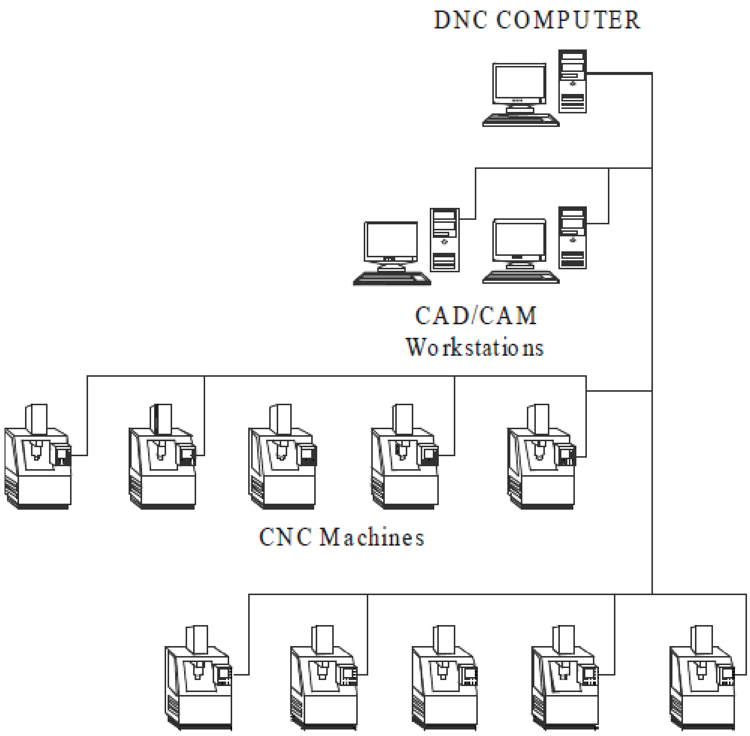
Figure 35: Steps involved in the CNC program creation on CAM.

We could say that for most of the steps from the manufacturing Model (CAM) to the CNC program creation, the work is being executed in the cyber world. The proposal considers the possibility of a CAM software to do the simulation in the cyber world and then, if the process there has no problems, it could be executed in the real world, following two procedures: first, the simulation on CAM is done, and then it follows the process execution on the CNC machine. The two procedures are not simultaneous.

With a new CNC tool with CPS implemented in the CNC machining area, complemented with a software package, will be pertinent to know how what are the implication of this procedure and what changes that could be done on CAM.

7.1 CAM communication

Nowadays the CAM system is commonly used to generate CNC programs. The communication between the CAM software computers to CNC machine is normally done through the DNC (Direct Numerical Control) computer. The DNC is a central computer who serves the CNC machine to transfer the programs for editing (Radhakrishnan, 2008). **Figure 36** shows the CAM on the system on DNC network.

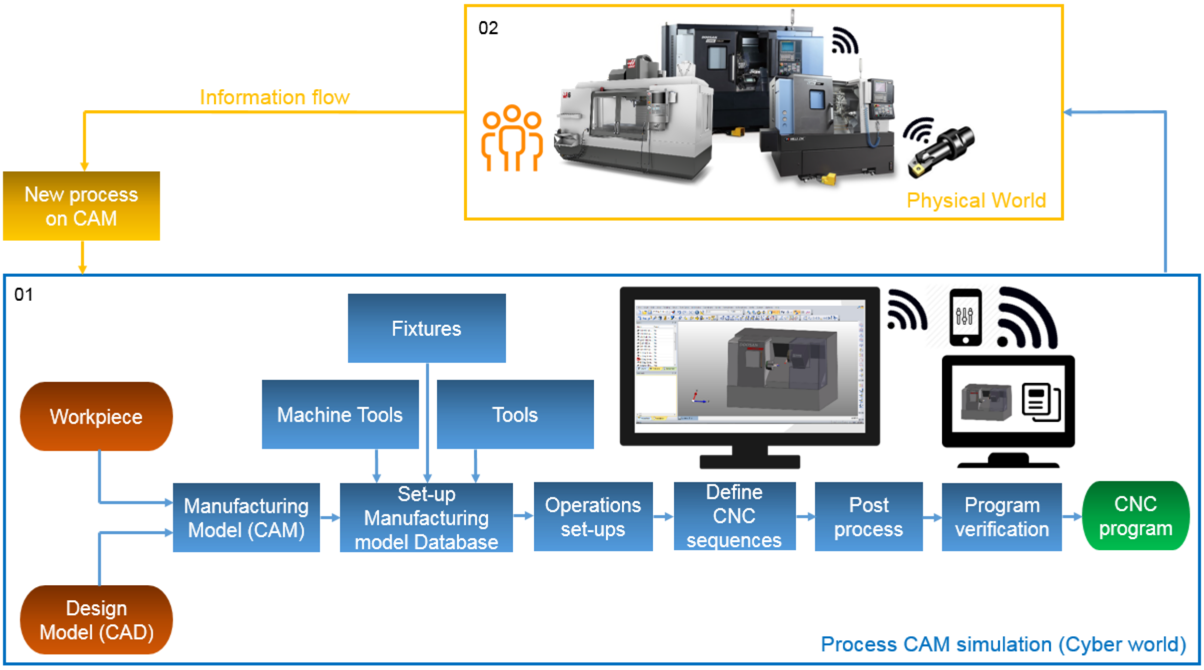


Source: (Radhakrishnan, 2008).

Figure 36: CAM workstation in DNC computer.

Over the years, other types of connection have been implemented and improved to transfer the programs to the CNC machine, such as, USB (Universal Serial Bus), Wi-Fi and Bluetooth connections. But the most commonly used is a DNC nowadays.

In the case of Sandvik Coromant, (2018), the tool with CPS provide a Toolguide software that communicates with CAM software, and there is a facility is to choose the ideal tool and parameters to do the simulation on CAM before going to the machine. This facility uses an open API (Application Programming Interface) and the possibility to the connection with the tool library and tool management systems on CAM. While programming on CAM, the programmer does not create a tool to execute the simulation on software, because it is already provided by on the Toolguide. So, the communication between the CAM software, CNC machine and the software of CNC tool still are not working in an integrated way and on real time when machining the physical workpiece. But it could help to decrease the time on process simulation on CAM software, giving the information about the process executed from the data and suggest parameters to use in certain materials. The architecture of the software interaction between the tools with CPS in communication with CAM could be seen in **Figure 37.**



Source: Figures retrieved from Sandvik, Doosan, Haas, EdgeCAM, Google images and altered by the author

Figure 37: Architecture of the software interaction between the tools with CPS in communication with CAM.

The information executed in real time could then be transferred to the software for future applications on CAM simulation. As the data could be saved on the Cloud during the process execution, the software with API (Application Programming Interface) connected with CAM could help the programmer when he is programming, facilitating with information about what is the ideal tool to be used in the process and the right parameters that could be used for specific materials.

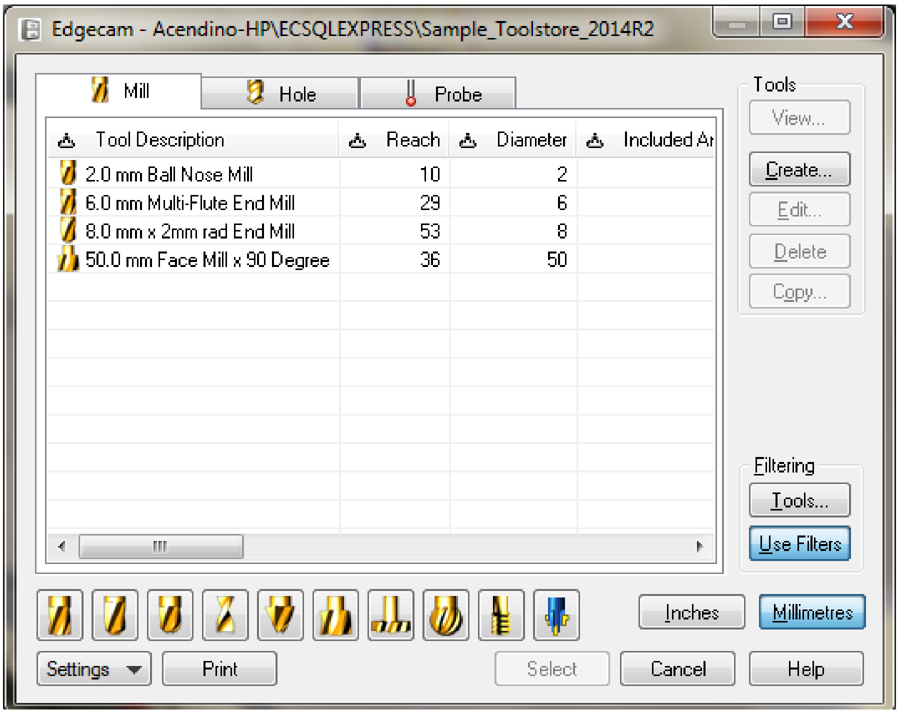
7.2 CAM functions

This topic analyzes the functions on CAM software and the possibilities of transformation on the workspace through the connection with the software from CNC tool with CPS.
For Dubovska et al., (2014), generally the CAM is a software associated with functions in manufacturing engineering, used to process planning and CNC programming, through the steps cited before on this topic by Radhakrishnan (2008) until the creation of a CNC program. With the implementation of the software from the tool with CPS in communication with CAM, the stage that could be most influenced by changes and improvements on CAM are:

- CAM Tool Library (Manufacturing set-up)
- CAM cutting operations (Operations set-up)

7.2.1 CAM Tool Library (Manufacturing set-up)

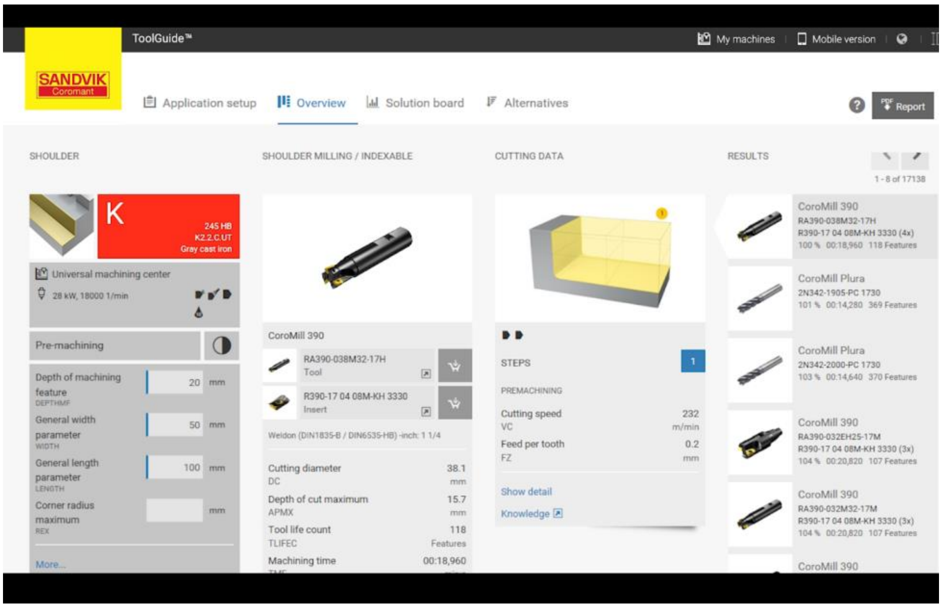
Manufacturing set-up is the stage where the programmer collects the information from the database on CAM and could make the set-up tools, choosing the ideal tool in accord with the operation to be executed. According to Radhakrishnan (2008), tools must be defined before an operation is performed. The tool library can be created when the operations are being executed on CAM or if the tool is already created could be taken from of the database. **Figure 38** shows the tool library from a software CAM.
The tool library on CAM is where the programmer creates the tool, giving all details and information about the tool shape. As there are lots of types of CNC tools, the programmer must create a tool on CAM very similar to the real world tool (physical tool), specifying the maximum details as possible. In the creation of tools on CAM, the programmer could make a new tool from initial stage or could use the information from a similar tool to create another one.



Source: Figure retrieved from EdgeCAM software.

Figure 38: EdgeCAM tool library as a CAM software

Through the tool library on CAM software, the software from the tool with CPS could be connected to the CAM with the API (Application Programming Interface), giving the virtual tool library of tools with CPS the possibility to use on virtually process execution for simulation (Sandvik Coromant, 2018). **Figure 39** shows the ToolGuide virtual workspace of the software from the tool with CPS where tools are already created.

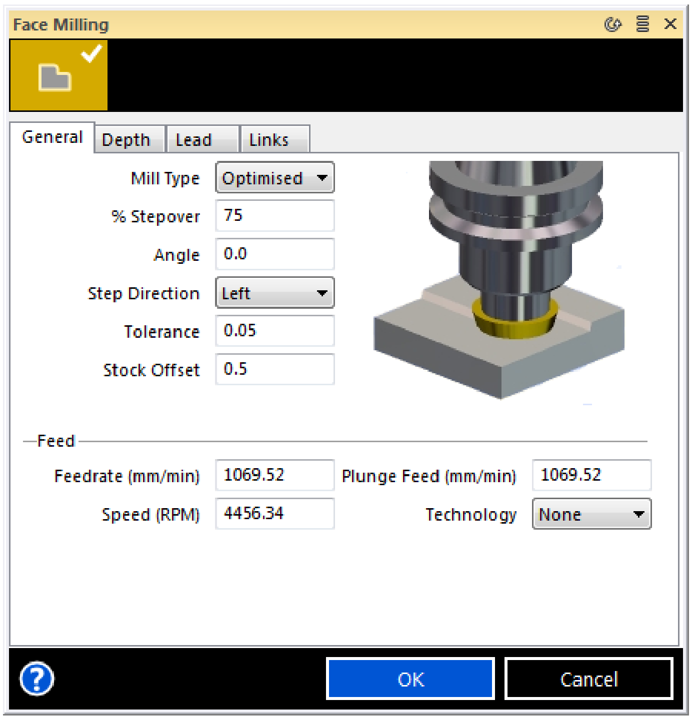


Source: (Sandvik Coromant, 2018)

Figure 39: Sandvik ToolGuide workspace.

7.2.2 CAM cutting operations (Operations set-up)

In this stage the programmer already has done the manufacturing set-up (machine, tools, fixtures, etc.) on CAM, keeping the workspace of the virtual world very similar to the physical world. Thereby, in operation set-up, the programmer will create a machinability database, specifying the parameters to cut the material, such as depth, speed and could be selected from the machinability database as shown in **Figure 40** in a CAM software. The program created will have this information. If some parameter is not right, this could be a problem with the machine. The ToolGuide software could connect to the CAM and suggest the right information so there would be no problem in the execution process in the real world.



Source: Figure retrieved from EdgeCAM software.

Figure 40: EdgeCAM cutting operations as a CAM software.

7.3 Advantages of process simulation on CAM in communication with the tool with CPS

The implementation of the software from the tool with CPS in communication with CAM has some advantages which will be explored in this section. Assuming the main function of tool set-up and operation set-up, the main advantages are:

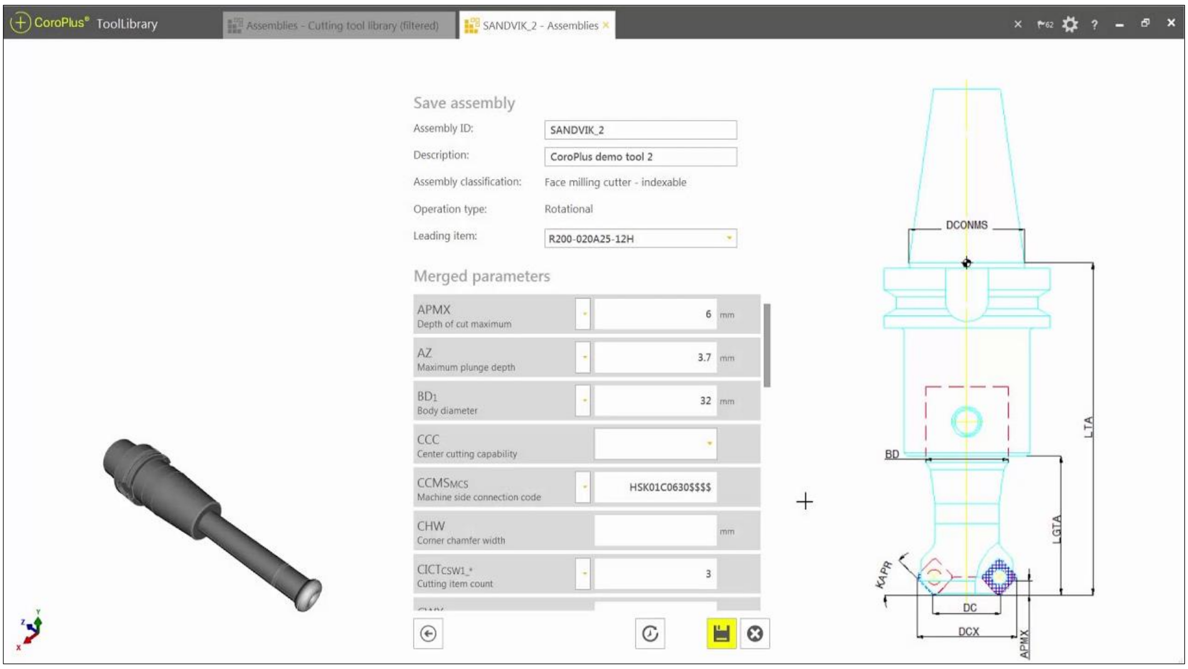
- No necessity to draw the CNC tool on CAM process simulation.
- No necessity to parameters calculation on CAM process simulation.

The followings section will elaborate on the two advantages.

7.3.1 No need to draw the CNC tool on CAM process simulation.

The manufacturing set-up stage is where the programmer collects the information from the database on CAM and could make the set-up tools, choosing the ideal tool in accord with the operation to be executed. In this stage of the actual process without the CNC tool software, the programmer takes or creates the tool to be used in CAM simulation, providing information as similar as possible to the physical world. The programmer must have the knowledge about which tool will be used (Radhakrishnan, 2008).

Through the tool library on CAM software mentioned in **Sub-Topic 6.2.1**, the software from the tool with CPS could connected to the CAM with the API (Application Programming Interface), giving information about the virtual tool library of tools with CPS to use on virtual process execution for simulation (Sandvik Coromant, 2018). The programmer could take and check on the library which tool can be used virtually on process simulation. Thereby, he does not need to create a CNC tool design virtually, because the tool is already provided by the software from CNC tool with CPS. The tools provided by the tool software are really advantageous because could save the time during process simulation on CAM, importing the direct design tool and the information needs through the software tool. **Figure 41** shows the tool design by the CNC tool software with the tools information.



Source: (Sandvik Coromant, 2018).

Figure 41: Tool design in Tool Library to import to CAM software.

7.3.2 No need to parameters calculation on CAM process simulation.

On operation set-up stage the programmer will create a machinability database, specifying the parameters to cut the material. All information filed by the operator on CAM is transferred to the program when generated on a post-processor. So, the calculation and the ideal parameters to fill the information on CAM is based on programmer's knowledge. The Speed and Feedrate are the essential calculations that have to be done by the programmer. These calculations are done following **Eq.(1)** and **Eq.(2)** and **Figure 42** shows the place where the programmer should fill the calculation information on CAM software.

The Speed (n) is calculated by **Eq.(1)** (Radhakrishnan, 2008):

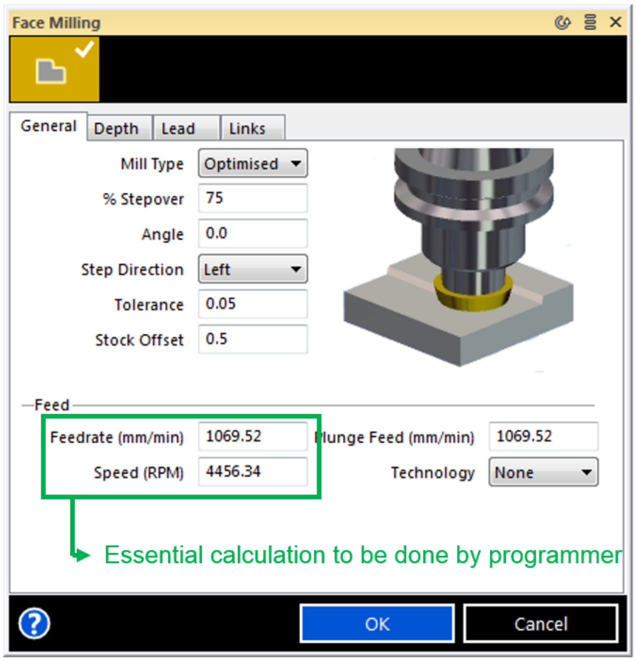
$$n = \frac{1000 \times V_C}{\pi \times D} \qquad \textbf{(1)}$$

Where n is the Speed of rotation per minute, V_C is Feedrate in meters per minute and D is the diameter of the cutter.

The Feedrate (S) is calculated by **Eq.(2)**:

$$V_C = \frac{\pi \times D \times n}{1000} \qquad \textbf{(2)}$$

Where V_C is the Feedrate in meters per minute, D is the diameter of the cutter and n is the Speed in rotation per minute.



Source: Figure retrieved from EdgeCAM software and altered by the author.

Figure 42: Workspace of CAM software to fill the Speed and Feedrate calculation.

So, the software from the tool with CPS connected to the CAM with the API (Application Programming Interface), provides the parameters information about Feedrate, Speed and other calculations that help the programmer with the right information and the programmer does not have to spend time with some basic calculations on process simulation (Sandvik Coromant, 2018). The essential information could be taken by the programmer on process simulation during the operation set-up on CAM.

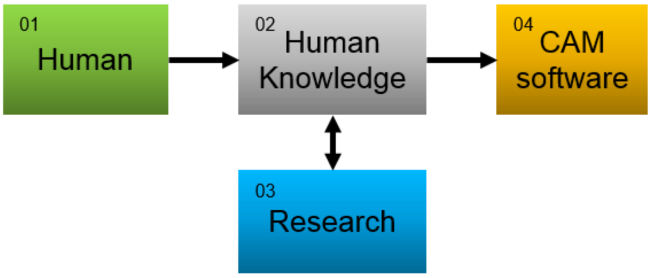
7.4 Impact on Human Labor

In the manufacturing process with the implementation of robotics and automated machines, the process was established in which automatable action sequences were performed by machines and non-automatable tasks continued to be performed by humans (Decker et al., 2017). Human intervention was subject to several modifications, guided by issues of production efficiency and reduction of human physical work.

Considering the effects with the CNC tool developed with the Cyber Physical System provided by a software that could connect to CAM by API (Application Programming Interface) and strictly checking the human labor changes with the implementation of this change, the perceived changes on human labor in this subject will be fundamentally based on **Sub-topic**

6.3 as mentioned before where some of the necessities will not be only depend on human labor to make the process simulation on virtual world.

Basically, nowadays without the CNC tool with CPS, the flow of information between humans and CAM can be seen in **Figure 43**.



Source: Elaborated by the author

Figure 43: Flow information from Human to CAM.

The flow information could be explained bellow:

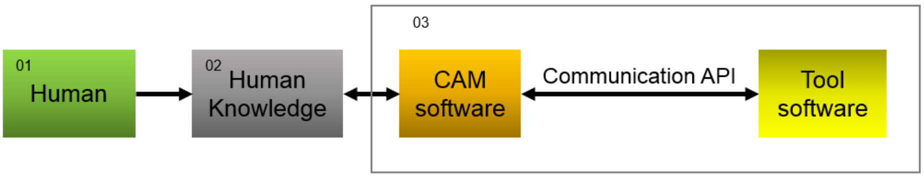
Phase 01- Human: The programmer who is programming on process simulation.

Phase 02- Human Knowledge: Is the knowledge of the programmer to transfer the information to CAM software, most of the time needs some personal knowledges in production, calculation and parameters. When the programmer has not an understanding about what is going on process simulation, there is a necessity to do a research (Phase 03) to get the ideal information.

Phase 03- Research: Research in external channels (books, internet, etc.) to acquire the necessary parameters information, calculation or make tool drawings similar to physical world.

Phase 04- CAM software: Is where the information is transferred to make the simulation on virtual world.

With the deployment of CNC tool with CPS providing a software that can help the programmer on process simulation, the architecture of the flow information is depicted in **Figure 44.**



Source: Elaborated by the author

Figure 44: Flow information from Human to CAM with tool software.

The flow information could be explained bellow:

Phase 01- Human: The programmer who is programming on process simulation.

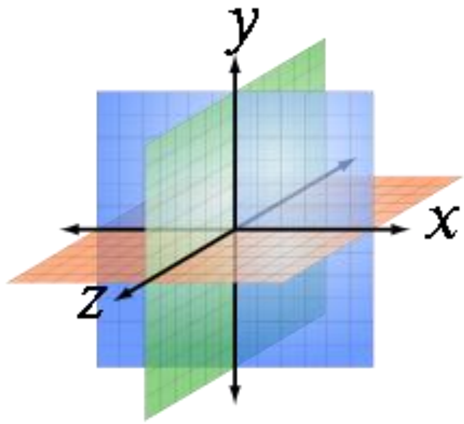
Phase 02- Human Knowledge: Is the knowledge of the programmer to transfer the information to CAM software, but now the human process knowledge could be advised by the software, the necessary information could be taken directly by CAM software (Phase 03), where the tool software is connected to the CAM and gives the necessary information to calculate, drawings and parameters to be used.

Phase 03- CAM/Tool software: The software is in communication with API, and the information about calculation, drawings and the ideal parameters to be used is already available on CAM.

Briefly, the tool software in communication with CAM could reduce the waste labor and time on process simulation execution, providing good information, design and ideal parameters to use on process. There is no dramatic impact on human labor, but there are some changes that can help the human on process development.

8. PROPOSAL FOR FUTURE PROCESS APPLICATIONS

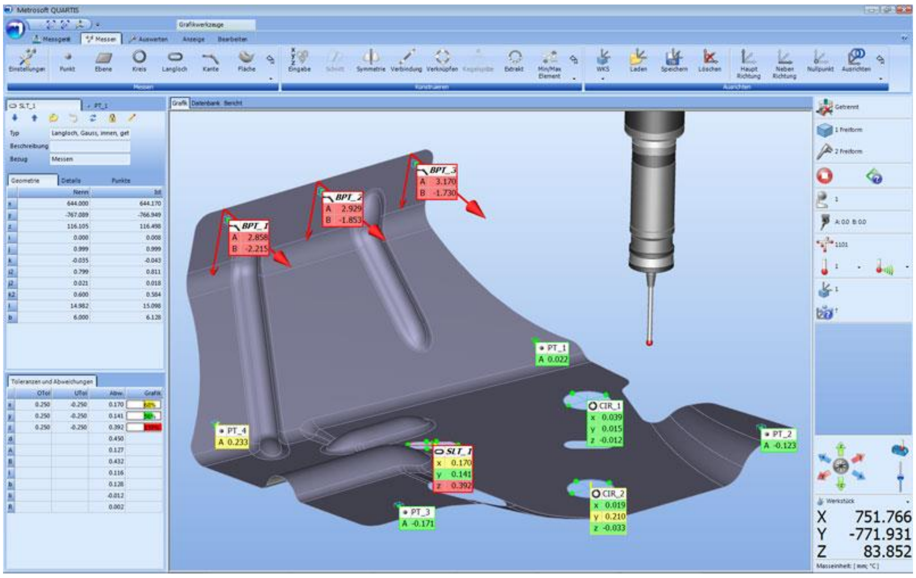
As it follows from the topics that were addressed in this study, the CNC machines are working centered on a three-dimensional space (X, Y and Z axes). The feed movement is to be realized by individual or simultaneous axes movement (Radhakrishnan, 2008). Thereby, the three-dimensional machines (machines for measurement), are based on a three-dimensional space as well. Some of them are called CNC Coordinate Measuring Machine, and are specifically designed for measuring components on the production line while keeping pace with modern machine tools (Mytutoyo, 2018). The three-dimensional space is shown in **Figure 45.**



Source: Figure retrieved from Wikipedia.

Figure 45: Three-dimensional space based on X, Y and Z axes.

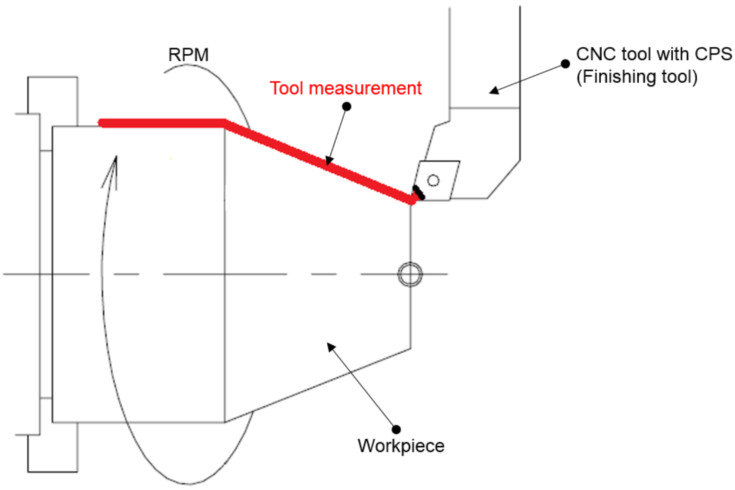
In addition to the **Sub-Topic 5.6.1,** where an original proposal for the tool measurement was made, the software from the tool with CPS could provide in the future similar information about measurement such as the machine's measurements provide nowadays. The most common process to make a measurement on a workpiece on the three-dimensional machine is collecting the point, through the sensors by the probe as can be seen in **Figure 46**.



Source: (Wenzel, 2018).

Figure 46: Three-dimensional software collecting the point of measurement.

For this project, the measurement will be not based on point collection using a probe as a sensor to collect the dimensions. The measurement will be done by the CNC tool with CPS during the process execution. Following the path of the axes previously programmed, the CNC tool could collect measurement information and transfer it to the CNC machine. The process measurement is a really sensitive process, where it needs a sensor (probe or CNC tool with CPS) to collect the information. The idea to do the measurement with the CNC tool is using the tool for finishing on process machining (tool used to remove small material and give the finishing on the surface). The way the finishing tool does the measurement and gives the finishing surface at the same time can be seen in **Figure 47.**



Source: Elaborated by the author

Figure 47: Finishing tool on lathe machine doing the measurement.

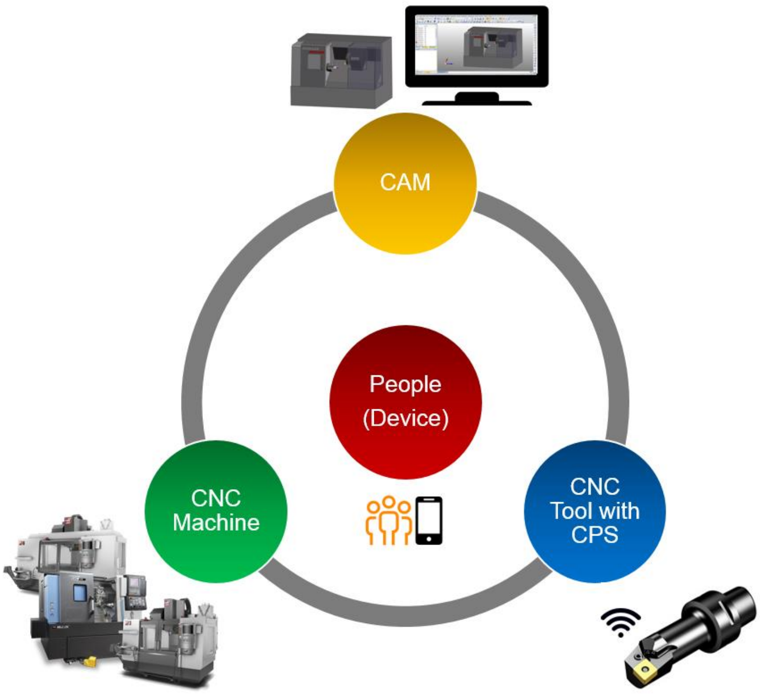
As the tool follows its path, the information could be transferred to the CNC machine. If the CNC software has the capacity of an automatic correction, the movements of the machine could compensate the variations of measurements transferred by the tool. In consequence, there will be no human intervention to make the measurement and no waste with machine stoppages.

Until nowadays, the measurement on CNC machines were not done because there were no CNC tools with capacity to transfer the measurement information during the process execution. The measurement information is done only by probe (sensor measurement) on physical contact. Since the new CNC tool with CPS has been implemented in the machining area with capacity to transfer the information during the process execution, this procedure could be done now.

9. STUDY AND ANALYSIS OF THE INTEGRATED PRODUCTION SYSTEM WITH THE TOOL WITH CPS, CNC MACHINE AND CAM SOFTWARE WITHIN THE CONCEPT OF INDUSTRY 4.0

As mentioned previously, a new tool with Cyber Physical System has been developed recently in the CNC machining area and it was explored how a CAM software works in communication between the tool with CPS and CNC machine, presenting the CAM possibilities of connection and effects. In this chapter it will be explored and analyzed how this production system works encompassing the tool with CPS, the CNC machine, a CAM software, and the concept of Industry 4.0.

The partial functionalities concerning communication interaction presented in **Chapter 5** and **Chapter 7** is now complemented. The aim is to show how this technology combination could work integrated through the communication architecture. The structure of the communication interaction working jointly can be seen in **Figure 48.**



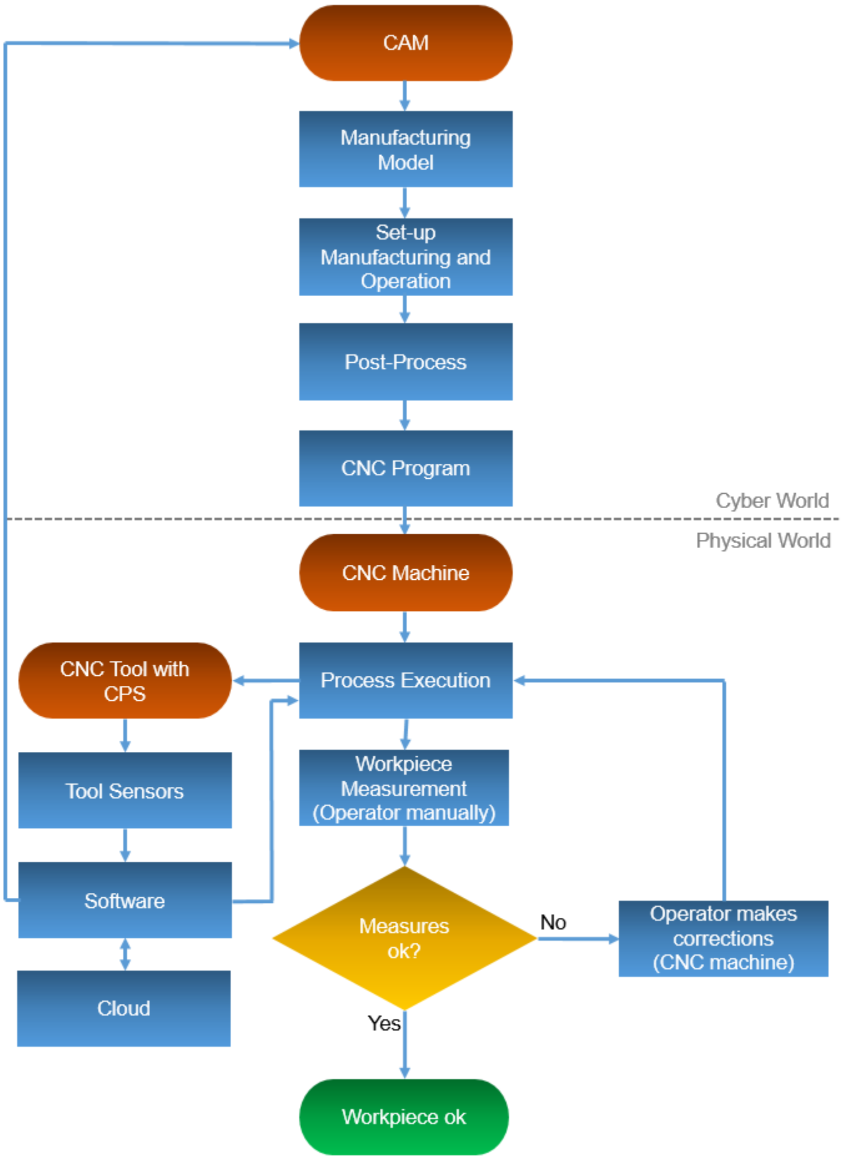
Source: Figure retrieved from Sandvik, Doosan, Haas, Google images and modified by the author.

Figure 48: Interaction communication between CNC machine, CNC tool with CPS and CAM.

This interactive communication provides a better process execution on the machining area. The technology combination of CNC tool with Cyber-Physical System, CNC machine and CAM software helps to transform the actual production processes on Industry 4.0 environment through the IoT (Internet of Things) and CPS (Cyber-Physical System), the interface of the physical world and cyber world.

9.1 Architecture communication between CNC tool with Cyber-Physical Technology, CNC machine and CAM

The combination of CNC tool with Cyber-Physical System, CNC machine and CAM software helps to transform the actual production processes on an Industry 4.0 environment. This subject will show how this technology combination could work viewed through the architecture flow information. The architecture flow information can be seen in **Figure 49.**



Source: Elaborated by the author

Figure 49: Flow information between CNC machine, CNC tool with CPS and CAM until the production of workpiece.

These technology combination is a new industrial production model compared to the traditional process, bringing the digital and physical world through the Cyber-Physical Systems (CPS) and Internet of Things (IoT) with the implementation of the CNC tool with CPS.

Analyzing the flow information architecture, starting with the CAM software, the flow shows the process simulation in cyber world until the creation of the CNC program, and then, the CNC program is transferred to CNC Machine. At the process execution on CNC Machine, the information is collected in real time (Physical World) by the sensors from CNC tool with CPS where this data is sent and stored on the Cloud and transmitted through the software from the CNC tool to CNC machine and CAM for the next production process.

The CNC tool with CPS works to transfer the information in real-time to the CNC Machine operator through the tool software and CAM. The CNC machine receives the information about the machine health behavior during the process execution. Thereby, the operator receives the information through the software about the machine health and machining behavior during the process execution (temperature and vibration), giving the information to the operator if something is going wrong. Thus, the operator could make the necessary changes. The CAM will receive the information about the process execution and tools used, and then, could be used for the next process simulation on virtual world.

9.2 Technology combination within the concept of Industry 4.0

As cited before by Platform Industry 4.0 (2017), the concept of Industry 4.0 fits into the current transformation process for the fourth industrial revolution, involving integrated Cyber-Physical Systems (CPS) within the manufacturing and logistics processes using the Internet of Things (IoT) and the Internet of Services (IoS) in industrial processes.

This new industrial paradigm brings the digital and physical world together through the Cyber-Physical Systems (CPS) and Internet of Things (IoT) and it is predictable some consequences for industry, namely improving production processes and increasing productivity, changing the work environment and restructuring the labor market (Pereira & Romero, 2017).

This combination of the technology with a CNC tool with Cyber-Physical System, CNC machine and CAM software, could transform the actual production processes on Industry 4.0 environment. With the CNC tool there is the capacity to transfer the information in real-time to the cyber world, and the process, the human and the machine could have a virtual and real interaction helping to increase the productivity and reduce the waste time.

The main purpose of Industry 4.0 is the creation of the smart factory, which are capable of managing process complexity, operate with less disruption, and more efficiently, through the interaction between humans, machines and resources resembling a social network (Kagermann et al., 2013)

For Pereira & Romero, (2017), the smart factory environment consists of a new integrative real-time intercommunication between every manufacturing resource that could help increase the manufacturing efficiency.

Talking about this technology combined with the smart factory environment of the Industry 4.0 concept, the sensors and software combination provided by the CNC tool with CPS allow an intercommunication between the real world and the cyber world, giving the information to the operator/manager about what is happening in real time manufacturing. Thereby, this change could improve the traditional manufacturing process, adapting in a smart manufacturing process the machining area. The main adaptations\transformations are:

- **CNC tool with CPS gives the information on process execution in real-time:** On traditional process execution using the normal CNC tool, there is no capacity to give information about what is going on the machining execution (Cutting temperature, roughness, vibration, etc.). As the CNC tool with CPS has been developed, it enables the capacity to transfer these information and transmit it to the software through the sensors and by Bluetooth connection with a device where the operator/manager has the possibility to verify the crucial points to manage or alter if necessary. Thereby, it creates a cyber virtual and real interaction, one of the topics on the Industry 4.0 concept (Kagermann et al., 2013), which are capable of managing process complexity, operate with less disruption, and more efficiently, during the interaction between humans, machines and resources.

- **CNC tool with CPS gives the information about CNC machine:** Similar to the previous point, in the traditional process execution using the normal CNC tool, there is no capacity to give information about machine health, although other technologies might help but not with a CNC tool. As the CNC tool with CPS has been developed, the capacity to transfer the information about the machine health has emerged, enabling the detection of the occurrence of some problem during the process execution on CNC machines. The CNC tool and CNC machine could work together through the software and hardware communication where the operator/manager has the possibility to verify the crucial points to do the maintenance or alter if necessary. This is another aspect of the concept of Industry 4.0. For Lee et al., (2015), in these networks, it circulates multiple information from different sources that are monitored and synchronized between the factory and cyberspace.

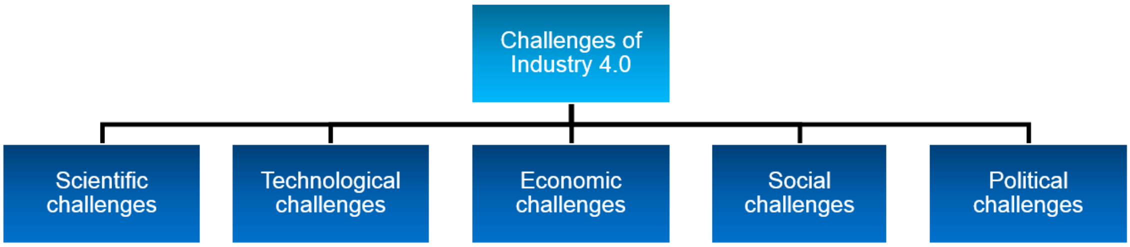
- **Human interaction on the process in real-time:** In the traditional process execution on CNC machine, there is not human interaction when the machine is working during the machining process. The human does not know what is happening during the process execution on machinability (turning, milling, drilling, etc.). The implementation of a CNC tool with CPS brings the possibility, if some problem occurs during the process execution on machine or tool, that the software gives the information to the operator and machine about what's happening in real-time (during the process machining), and the operator could make or provide the changes without stopping the machine (at least in some cases).

- **Cutting tool information saved on a cloud:** In the actual conditions of using the traditional mechanical CNC tool, there is no capacity to save the cutting information on the cloud. Instead of it using the CNC tool with CPS during the process execution in real-time, it is possible to save the information on the cloud, and there is the possibility to save the actual information on the process to use in the future productions with similar characteristic. For Chen (2014), the intelligent processing will support IoT applications by collecting data from databases, various intelligent computing technologies, including cloud computing. Network service providers can process a large volume of messages instantly through cloud computing.

- **CAM Software supported by CNC tool software on virtual world:** The software from the tool with CPS could connected to the CAM with the API (Application Programming Interface), giving the possibility to use the virtual tool library of tools with CPS on virtual process execution for simulation. On operation set-up stage the programmer will create a machinability database, specifying the parameters to cut the material. All information filed by the operator on CAM is transferred to the program when generated on a post-processor. For MacDougall (2014), the interaction between systems based on high-performance software and dedicated user interfaces, integrated with digital networks, create a new universe of functionalities for systems on Industry 4.0.

9.3 Challenges in Industry 4.0

It is not an easy thing to achieve the concept of Industry 4.0 on production systems. Nowadays, this concept is a future possibility. The concept faces many types of difficulties and challenges, such as scientific challenges, technological challenges, economic challenges, social problems and political issues (Zhou, Liu, & Zhou, 2016). A brief introduction of these challenges in Industry 4.0 is given in **Figure 50.**



Source: (Zhou et al., 2016).

Figure 50: Different Challenges of Industry 4.0.

The main science and technology challenges of the Industry 4.0 concept are, according to Zhou et al., (2016):

- The development of smart devices
- The construction of the network environment
- Big data analysis and processing
- Digital manufacturing

The followings sections will elaborate on the challenges.

9.3.1 The development of smart devices

Production operations in the Industry 4.0 factory is a more intelligent system than at any factory we have ever known. Thus, it requires more intervention from artificial devices, automated machines and robots, consequently reducing human labor intervention. However, different types of production in the factories need different smart devices configurations and development requiring much time and money before it starts to work effectively on production in Industry 4.0 factories (Zhou et al., 2016). In this project, regarding the CNC tool with CPS developed by Sandvik, the tool technology needs a communication with a smart device that consequently increases the product price.

9.3.2 The construction of the network environment

For Zhou et al. (2016), the network environment in Industry 4.0 mainly refers to a CPPS (Cyber-Physical Production System) platform using CPS technology. Building the CPPS Platform, is a multifaceted project in development and has various limiting conditions from CPS challenges, which are:

- **Cooperation between different systems:** Considering the relationship between the physical systems and the cyber system. By the perspective of the physical environment, a CPS has spatiotemporal properties, and computer systems need to ensure accurate, real-time decision-making and process control of the event handler to ensure accurate control of the physical system control time and space. So, the interaction through the physical system and the information network system need to be considered. The information network systems achieve ubiquitous communication access, which enables physical devices to exchange information. It is necessary to consider the cyber system and information network interaction. The physical devices for security purposes have object-oriented and reliability requirements, for a general purpose they are different from a computer system. Thereby, there is a need to study the dynamics of the physical system and each reconfigurable, sequential and discrete computational system, and the abstract information network system (Zhou et al., 2016). Regarding this point, and focusing on this project, the communication between CNC tool with Cyber-Physical System, CNC machine and CAM software require an exchange of physical systems and the information network system.

- **CPS modeling and model integration:** The CPS is the interaction of the cyber and physical process, considering their behavior when merged. A cyber world on CPS model needs to consider the physical environment, through the software and hardware platforms, and network models as well as any further scheduling software required, network delays, power consumption and other functional and non-functional factors. The characteristics of CPS must be considered since the interaction of the cybernetic and physical world involves several different types of computational models. The calculation process uses a discrete logical time, while the physical process uses the continuous physical time. Events in the computing world often refer to messages, exceptions, or interruptions, but events in the physical world probably refer to position, shape, and other physical properties. It is difficult to use a variety of computing models to build a CPS model with a unified structure. A development of a new CPS modeling language to adapt to the complex environment is still necessary. Modeling and integrating CPS models are still a challenge (Zhou et al., 2016). In the analysis of this work studying the tool provided by the Cyber-Physical System it was observed that the computing world often refers to limited information on process execution and the information is not still complex compared to the physical world. The model integration could be maximally improved to make the cyber world more similar to the physical world.

- **The integration of CPS:** According to Zhou et al. (2016), the integration of the CPS includes integration of heterogeneous components, integration of methods, and integration of tools. One of the challenges is how to design a flexible interface for different components and adaptive combination between components. Thus, the CPS includes many fields to be considered, and each field has a self-contained set of models, languages and methods. The design and development of CPS need a complete tool chain to support CPS modeling, simulation, analysis, synthesis, and the development of various computing and communications components. The tool with CPS studied in this dissertation, is one part of the integration of Cyber-Physical System on an Industry 4.0 environment. The tool has already provided a large scope for studies and is just one part of the flow information on CPS considering the production of a smart factory.

- **Verification and testing of CPS:** The CPS is extremely complex because there are different heterogeneous components working. It develops an important part in the system. Thus, the CPS requires rigorous testing and validation prior to its application, so that the system is satisfactory for each application, ensuring that it is designed to meet the demands. Uniform standards and specifications for CPS verification and testing are not yet available. Despite of it, there are no uniform standards and specifications for verification and testing of the CPS in general aspect (Zhou et al., 2016). For the CNC tool developed for CPS it was created the ISO 13399, which is the international technical standard for information exchange between various software servicing cutting tools and holders, and between tool manufacturers and suppliers.

9.3.3 Big data analysis and processing

In Industry 4.0, all equipment, machinery, production, applications, products and services will continue to generate data, which are by nature large and complex. Data analysis in the industrial production process and efficient integration in real time must be ensured to optimize the resources in the production chain. In the meantime, it should be addressed the fact that big data introduces issues of protection and privacy of corporate information, and information security issues. Nowadays the research and applications in the industrial big data field are not particularly mature in all areas, from hardware to software, and need additional improvements (Zhou et al., 2016). On production with CNC machine in machining area, the efficient integration in real time and data analysis in the industrial production process, and the resources in the production chain, need to be optimized as well to ensure the information flow security.

9.3.4 Digital manufacturing

Nowadays, digital manufacturing construction is maximizing the use of scanning, simulation, and Internet technologies for hardware integration, software integration, and a consolidated database. During this implementation process many technologies, management, standards and other difficulties will be encountered. As the digital world and the physical world become integrated, network security issues are becoming increasingly serious for digital manufacturing. Many problems will have to be solved regarding network security and how cybernetic espionage should be addressed to prevent hackers and other cybercrime to introduce disruptions to the system (Zhou et al., 2016).

10. FINAL PROPOSAL FOR A NEW PRODUCTION MODEL

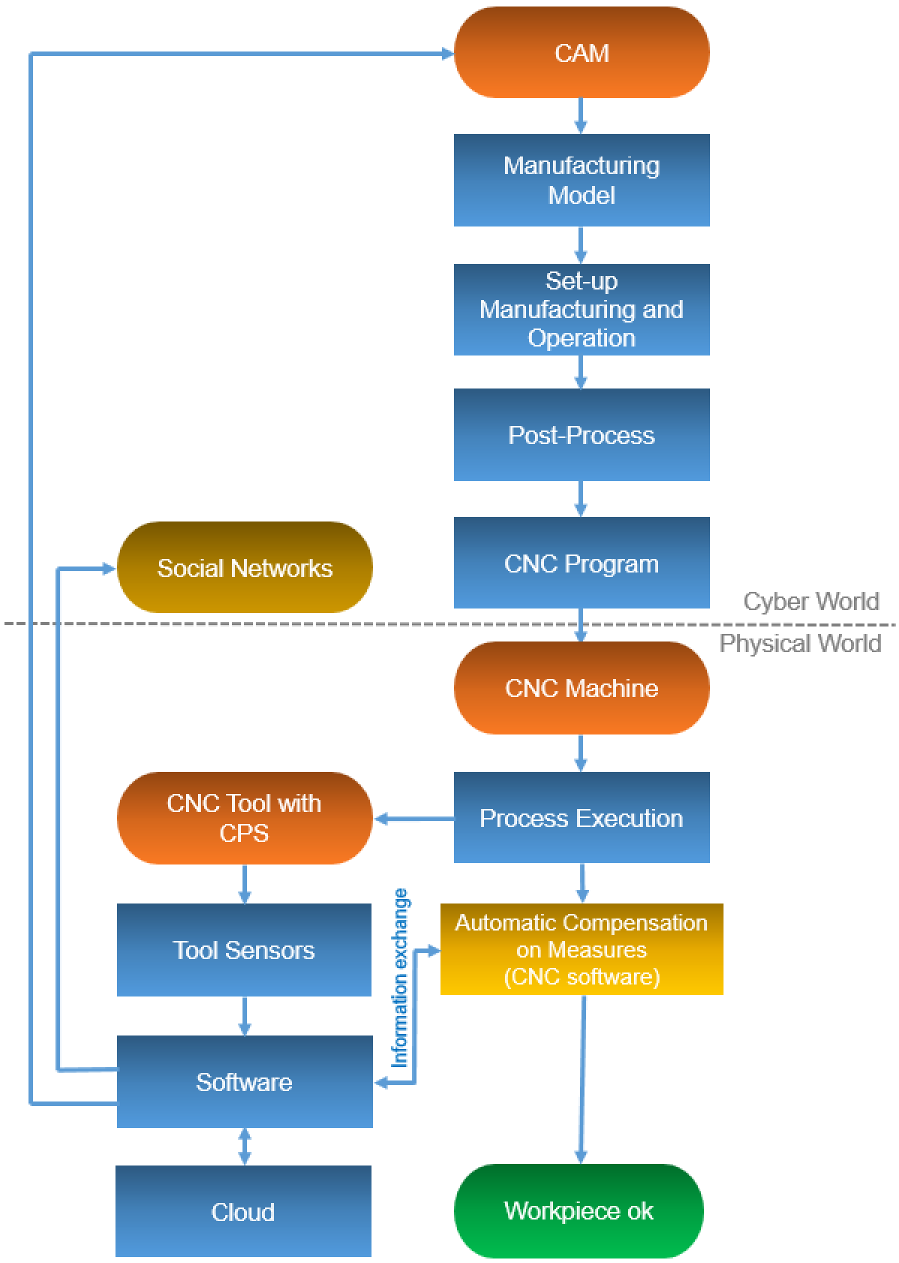
Following the main objective of this project and following the proposals presented on **Chapter 6** and **Chapter 8**, this chapter presents a general proposal for a new production model and a better system production for machining areas. This final proposal will show how this new production model could work encompassing the tool with CPS, CNC machines and CAM software in a better way than existing models, and will show the new idea of communication interaction between them. For the development of this topic, reference will be made to the following points:

- Idea architecture
- Idea development
- Advantages in production
- Impact on human labor
- Challenges on idea implementation

The following sections will elaborate on each one.

10.1 Idea architecture

During the development of this work on the Industry 4.0 concept in machining area, it emerged an idea of a new model production that can help in bettering production and reducing waste that comes from machine stoppages. The architecture of the proposed idea for this project can be seen in **Figure 51.**



Source: Elaborated by the author

Figure 51: Proposal of architecture of flow information between CNC machine, CNC tool with CPS and CAM during the process production of workpiece.

The explanation of the proposal of the architecture follows: first, it starts the communication flow by the CAM on the cyber world, and the process simulation is keeping the same steps of the present processes using the CNC tool with CPS until the creation of a CNC program. The information processed in real time (by CNC tool with CPS) could be transferred to the software for future applications on CAM simulation. As the data could be saved on Cloud during the process execution, the software with API (Application Programming Interface) connected with

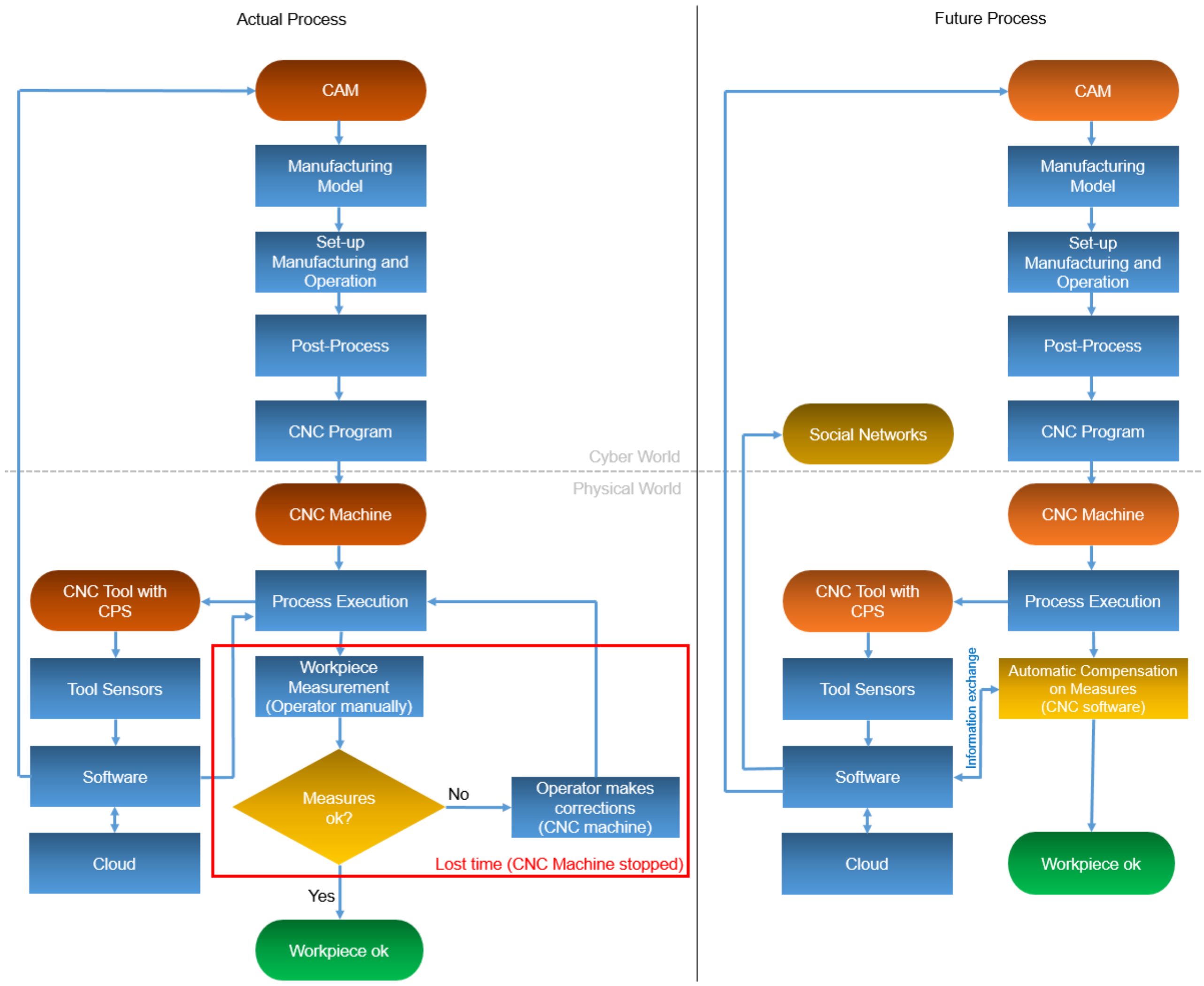
CAM could help the programmer when he is programming, facilitating with information about what is the ideal tool to be used in the process and the right parameters to be used for specific materials.

Then, the CNC program is received by the CNC machine for process execution in the physical world. As the machine is already prepared for process execution, the CNC tool with CPS and CNC machine start to work together. The sensors from CNC tool collect the information during the process execution, keeping it on the Cloud, then through the software, the information is transferred to CAM for future simulations, to the social network (a new feature, presented in one of the previous proposals) and is keeping the communication integrated with the CNC machine for information exchange.

The communication with a social network embodies the possibility of CNC tool with Cyber Physical System in communication with IoT (Internet of Things), the CNC tool could communicate with the social networks (Facebook, Twitter or LinkedIn), where they could create some groups to discuss about the problem in real time or post as a discussion.

The information exchange between CNC tool and CNC machines, and the respective softwares could work in an integrated way giving the information about the measurement on process execution through the sensors, and the software and hardware connected to the CNC machine have a capacity to make the automatic corrections during the process execution in real time. In other words, through the information collected by the sensors, the tool and CNC machine could work together. So, the lost time in the measurement process in CNC machine would not exist.

Figure 52 shows the difference between the actual process using CNC tool with CPS and the proposal for the future process, eliminating the waste time with machine stoppages.



Source: Elaborated by the author

Figure 52: The different architecture between the actual process using CNC tool with CPS and the proposal for the future process eliminating the waste time with machine stoppages

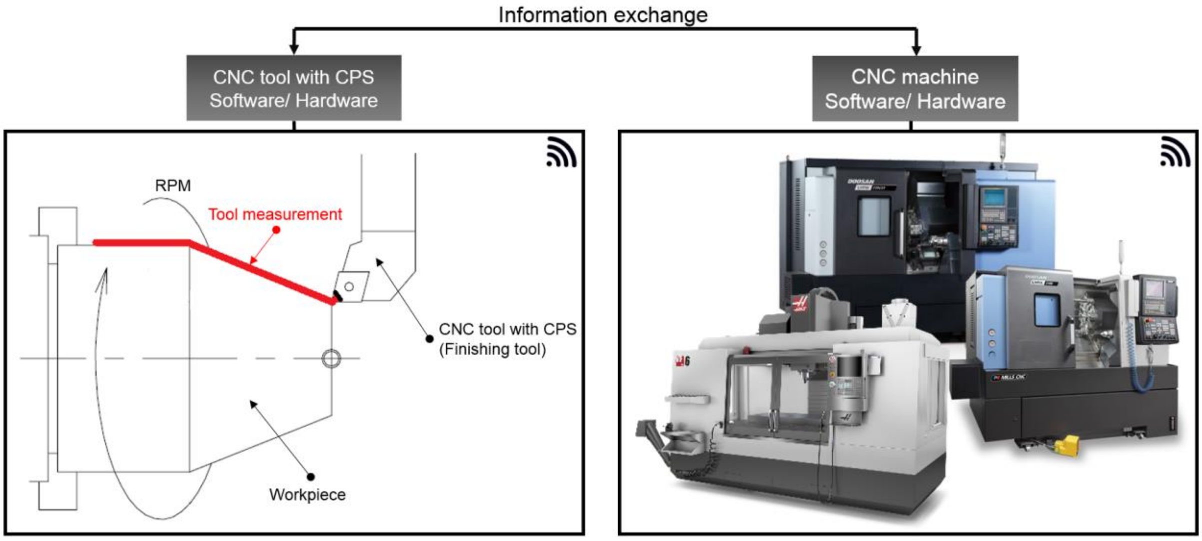
10.2 Idea development

In the process execution on CNC machines using a CNC tool with CPS, the tool has the capacity to send the information about roughness, vibration, cutting and temperature. Thus, the development of the proposal and following the proposed architecture, consists in the implementation of two main dimensions, the tool measurement and the communication with social networks through the tool with CPS. The tool could collect the information about measurement and work together with a CNC machine to make the automatic corrections.

The proposal for tool measurement on CNC machines is to use the CNC tool with Cyber Physical System giving the information about the measurement on process execution through the sensors, where the workpiece could be measured during the process execution and when the process is done, the workpiece would be already measured, and no time would be lost with machine interruptions.

The tool would follow the programmed axes path during the measurement, collecting measures information and transfer it to the CNC machine through the software and hardware. The process measurement is a really sensitive process that needs a sensor to collect the information. The idea to do the measurement with the CNC tool is using the tool for finishing operation with less removal of material on process machining.

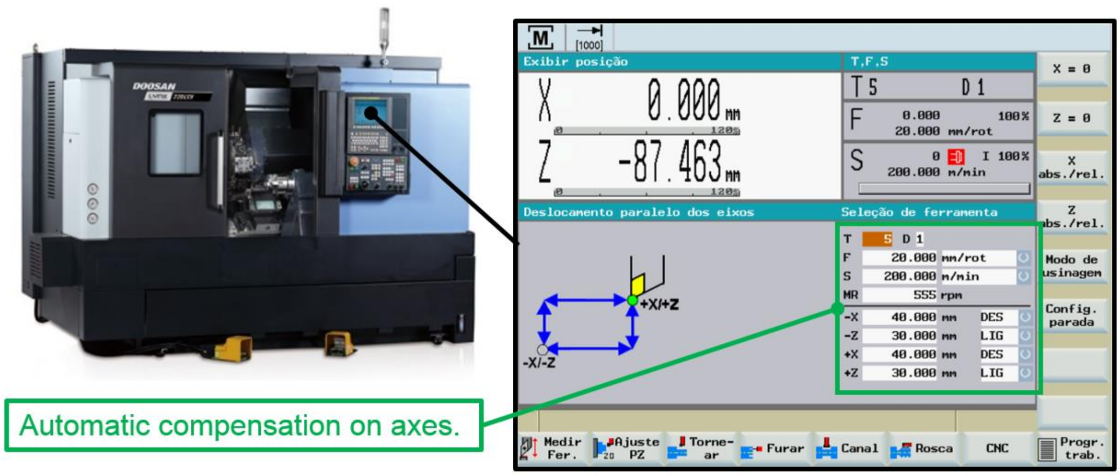
The tool software will send the information collected by the tool sensors to the software and hardware of the CNC machine as shown in **Figure 53.** Thereby, the software of the CNC machine has to be modified compared to the actual software on CNC machines. The machine software has to be able to collect the information on real-time and make the changes automatically. This is one of the most important steps for the development of this idea. The software will communicate with the tool making the automatic compensation. CNC machines are working centered on a three-dimensional space (X, Y and Z axes) and the three-dimensional machines work in three-dimensional space as well to make the measurements. This possibility is viable for development, will be a technology combination between the software from CNC machine and three-dimensional machines. The software from the tool and the machine will work in articulation with each other, exchanging information about measurement during the process execution. We know that during the process execution there are numerous parameters to be considered, such as material, RPM, speed, insert, among other aspects that could influence the process execution. Thereby, the initial step to implement the proposal is to do the measurement of the basic process execution on CNC lathe machines for finishing surfaces, as a first implementation, test and analysis of the proposed idea.



Source: Figure retrieved from Doosan, Haas, Google images and modified by the author

Figure 53: Information exchange between CNC tool with CPS and CNC machine during the measurement.

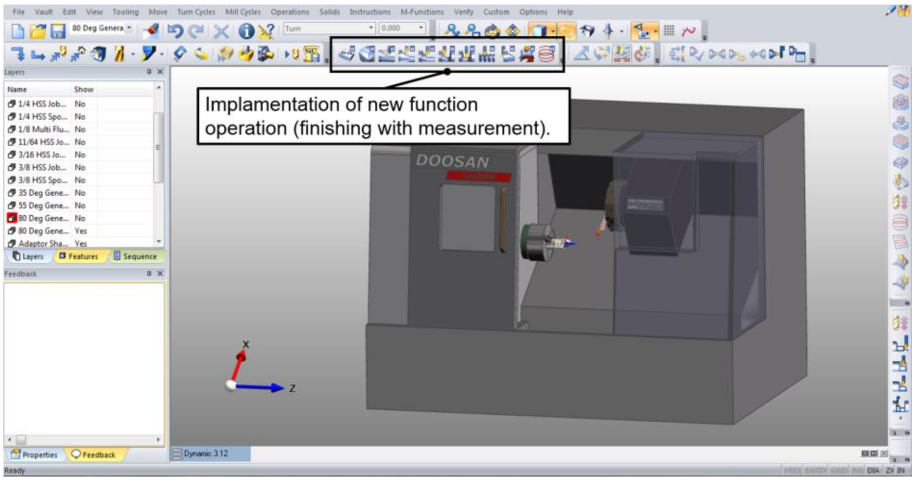
The software of the CNC machine will have the capacity to interpret the measurement as the three-dimensional machine works, answering automatically to the changes during the process execution (finishing with measurement). This process will consist on the adaptation of the actual software on CNC machine software, because the actual software is not able to do the automatic corrections, because there was not a CNC tool with the capacity to do the measurement during the process execution. The proposal for the software adjustment could be seen in **Figure 54.**



Source: Figure retrieved from Doosan, Siemens and modified by the author.

Figure 54: Automatic compensation of CNC machine software.

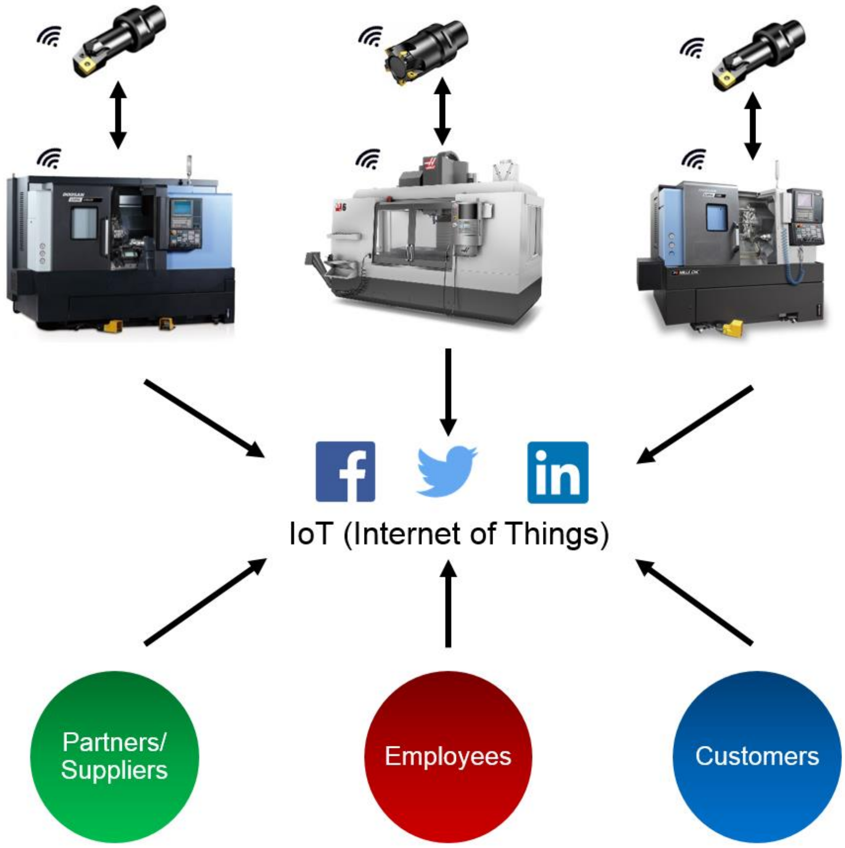
Thereby, and as a consequence on the process simulation using a CAM software in the cyber world, it could be created a new operation function, the operation of measurement where the programmer could select this function to do the simulation on the virtual world. **Figure 55** shows how this proposal operation could be selected on CAM.



Source: Figure retrieved from EdgeCAM software and modified by the author.

Figure 55: Implementation of a new operation on CAM (finishing with measurement).

Following the architecture proposal, and regarding the implementation of communication with social network, as the CNC tool with CPS is provided by IoT (Internet of Things), the tool could communicate with the social networks (Facebook, Twitter or LinkedIn), where they could create some groups to discuss about problems in real time or post as a discussion. The company could use the information collected by the tool and share a discussion on groups on social networks, between employees, partners or customers, increasing the chance to solve the problem through the knowledge from the people on networks. The discussion group could be managed by the company. The option to create an internal group or an open group on social networks, will be the choice of the company. This possibility with the connection with social network could help with advertising and marketing, showing the actual process of the company, about solutions on real time and the process execution. Another advantage of using social networks could be the ability to send messages when the workpiece is done, after the process execution is concluded, and the people on social networks will know when the workpiece is done or when it is going to the next operation, facilitating production control. **Figure 56** shows how this process could work through the social network connection.



Source: Figure retrieved from Sandvik, Haas, Doosan, Google images and modified by the author.

Figure 56: Process interaction through social network.

10.3 Advantages in production

Building on the study and analysis made along this project and following the proposals presented, it will be highlighted below the main advantages that the proposals and their implementation bring to production systems. The main advantages are:

- **Reduction of waste in time due to machine stoppages:** This is one of the main advantages in production. As the CNC tool with Cyber Physical System could transfer the information about the measurement on process execution through the sensors, where the workpiece could be measured during the process execution and when the process is done, the measurement of the workpiece would be concomitant to its production and there would not be interruptions and time lost. The time that the operator spent measuring the workpiece will be done by CNC tool through the CNC machine, and the time on reading and verifying the measures manually will not be necessary because it will be done automatically. That is a really important waste reduction because could influence directly costs during the process.

- **Reduction of the use of measurement instruments:** As the CNC tool with CPS has the capacity to transfer the information about the measurement on process execution through the sensors, the workpiece could be measured during the process execution. The measuring instruments are delicate and require a certain concentration by whoever is doing the measurement, and several aspects during the measurements require high precision, which consequently requires a certain time to perform the process. The costs with measurement instruments will be decreased because there will be no necessity to use the instruments to verify the measures.

- **Internal company departments and external partner interaction on production:** This advantage relates to the architecture process, for implementation of communication with social networks. As the CNC tool could communicate with the social networks (Facebook, Twitter or LinkedIn), the company could improve the management of the interaction between all internal departments related to production and the external partners or suppliers. The company could create some groups to discuss about problems in real time or post as a discussion, and consequently getting a faster solution to the problems that eventually occur.

10.4 Impact on Human labor

During phases of technological development and technology advancement, the relationship between human and machine are changing over time, and both are substituted or complemented in complex ways during historical development. Following the proposal of idea architecture presented in this work, there is an impact on human labor, particularly due to the effects of the implementation of CNC tool developed with the Cyber Physical System, which has the capacity to collect the information about measurement and could send the information on social networks if some problem occur. The changes on human labor due to these effects will be smooth and gradual, because only some of the necessities will not be exclusively dependent on human labor to make, during the process execution. The impacts on human labor are:

- **There is no necessity of the operator to make the measurement on the workpiece during the machinability on process execution:** Using the CNC tool with Cyber Physical System, which gives the information about the measurement during process execution through the sensors, the software will provide the measurement on the workpiece, and the work to measure that was executed by the operator will not be necessary because the measurement will be executed automatically by machine.

- **The problems occurred during the process execution could be controlled virtually:** This advantage follows from the architecture process for implementation of communication with social networks. Since the CNC tool could communicate with the social networks (Facebook, Twitter or LinkedIn), the company could make the interaction between all internal departments related to production and the external partners or suppliers. The company could create some groups to discuss about the problem in real time or post as a discussion, and consequently the problems could be controlled virtually to find one solution. This implementation could help in problem solving without the necessity of the human displacement of internal or external necessities.

10.5 Challenges on idea implementation

The challenges on the concept of industry 4.0 are not an easy thing to achieve. Nowadays, this concept is a process mostly to be implemented in the (near or not so near) future. There are many aspects to be developed, improved and implemented. Concerning the architecture proposal presented in this work, it will be no different. There are some challenges on this topic and the most important ones for the implementation of this proposal are:

- **Cooperation between different systems, CNC machine software and CNC tool software:** It concerns essentially the tool measurement through the tool with CPS following the idea architecture. The tool could collect the information about measurement and work encompassed with a CNC machine to make the automatic corrections. To make it happen, the software from tool and machine need to work together, different systems should be working in an integrated way. A new programming interface between both software packages has to provide the ability to communicate between them. Thus, using the CNC tool with the Cyber Physical System giving the information about the measurement on process execution through the sensors, the software from tool and machine has to be able to make the compensation on axes automatically during the process execution.

- **Implementation of a new function operation on CAM:** The CNC tool with CPS and the CNC machine start to work together during the process execution. The sensors from the CNC tool collect the information during the process, keeping it on the Cloud, and then through the software, the information is transferred to CAM for future simulations. But on process simulation on CAM, as there is a new function operation, as mentioned before, which was called "finishing measurement", as one of the proposals in this work, to make it happen a new operation should be created on CAM software, giving the possibility of coupling finishing (already available on CAM) with measurement operation. It will be an option to select the information about measurement and what kind of measures to be done (internal or external measures).

11. Conclusion and Outlook

11.1 Conclusion

The work related to this dissertation consisted of an analysis of the technological evolution of the machining processes with CNC machines, having in mind the new concept of Industry 4.0. In order to reach it, a thorough study has been done to adapt the methodology of Industry 4.0 applying it to the machining processes in CNC Machines.

One of the main factors that influence the development of machining processes in CNC machines are the tools used in CNC machining processes for production. Therefore, a deep study of the issues related to the technological evolution of the tools used in CNC's with virtual technology has been done. A better understanding of how the virtual technology works with machining tools on CNC machines has been done. During the development of this study, it was possible to analyze the main factors that can influence directly or indirectly the production processes of a factory with CNC machines.

Considering that the requisite "CNC machining tools" was one of the main factors that can affect the execution of machining processes on CNC's, an exploration and study of the types of machining processes for CNC machines and the types of machining tools developed with virtual technology has been executed.

This study enabled a better understanding about virtual technology addressed by software on machinability. As a new tool with Cyber-Physical System has emerged in the CNC machining area, a better understanding of how this tool could work on CNC machines was presented. Thereafter, it come up the opportunity to study how a CAM software works in communication between the tool with CPS and the CNC machine, presenting the CAM possibilities of connection and effects. A study and analysis of how this production system works in an integrated way between the tool with CPS, the CNC machine and CAM software within the concept of Industry 4.0 has been done, to give a better understanding of how this recent technology implementation of machining processes could be adapted under the concept of Industry 4.0.

Finally, following the original proposals presented in the chapters regarding the integration of CNC tools and machines, a general proposal for a new production model has been presented for a better production system in the machining area. This proposal showed how this new production model could work integrating tool with CPS, CNC machine and CAM software, giving a new idea of communication interaction between them.

11.2 Outlook

In order to keep the development of the presented proposal, the following are some suggestions for future work:

- Development of the programming software to communicate with CNC machine and CNC tool with CPS to make the automatic compensation during the process execution.
- Development of interface programming on CAM software for the implementation of a new function operation on CAM, giving the possibility to finish and measure the surface at the same time on process simulation (virtual world).
- The implementation of a new production system on CNC machines processes enabled by technical evolution using a CNC tool with Cyber-Physical System, and the analysis of the challenges, impacts and adaptations to be done within the concept of Industry 4.0.

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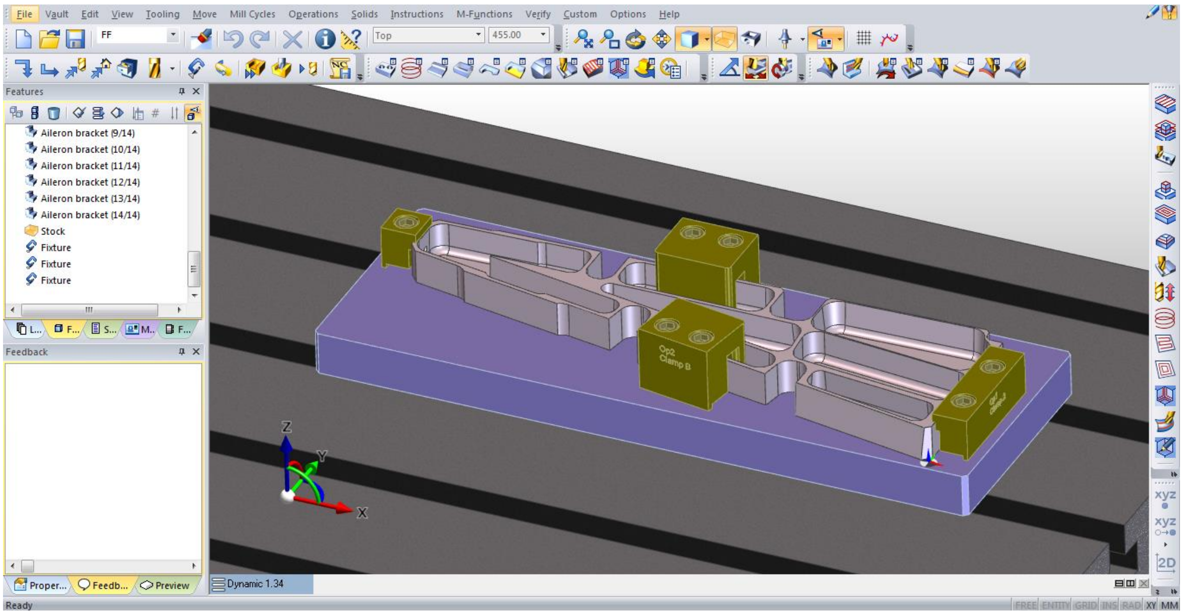
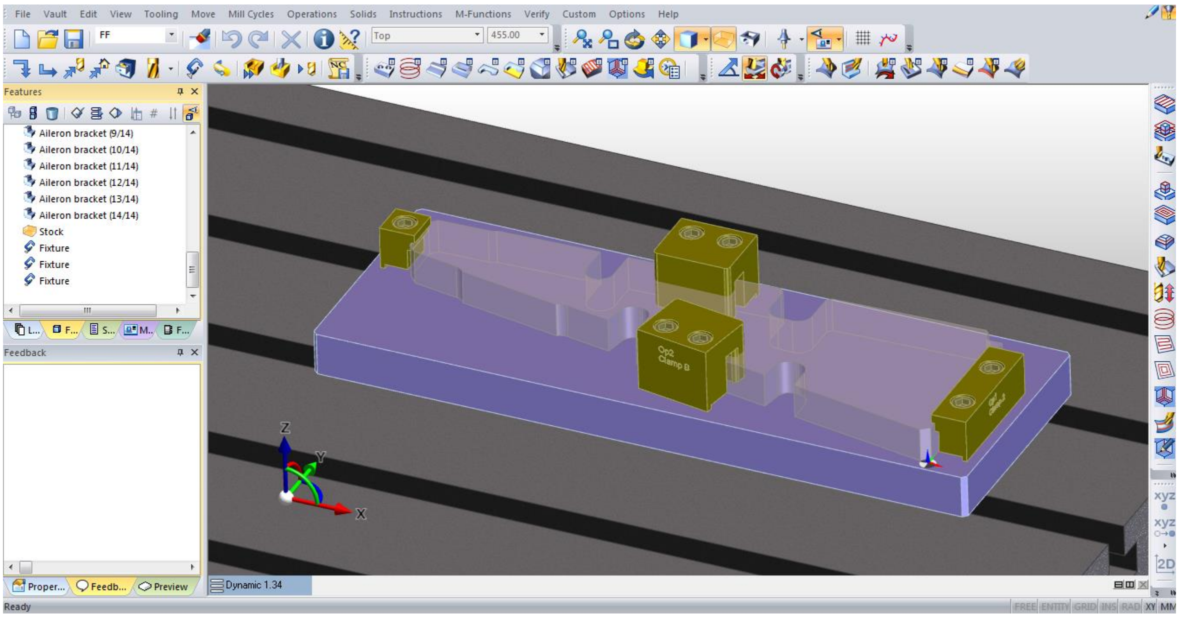
APPENDIX I – CREATION OF A CNC PROGRAM THROUGH THE EDGECAM CAM SOFTWARE

Example of the creation of a CNC program with G-codes using a CAM software. The CAD model represents the finished product. This is used as a basis for the manufacturing operations. The workpiece is the raw material from which the component is obtained after the manufacturing operations.



Source: Figure retrieved from EdgeCAM software

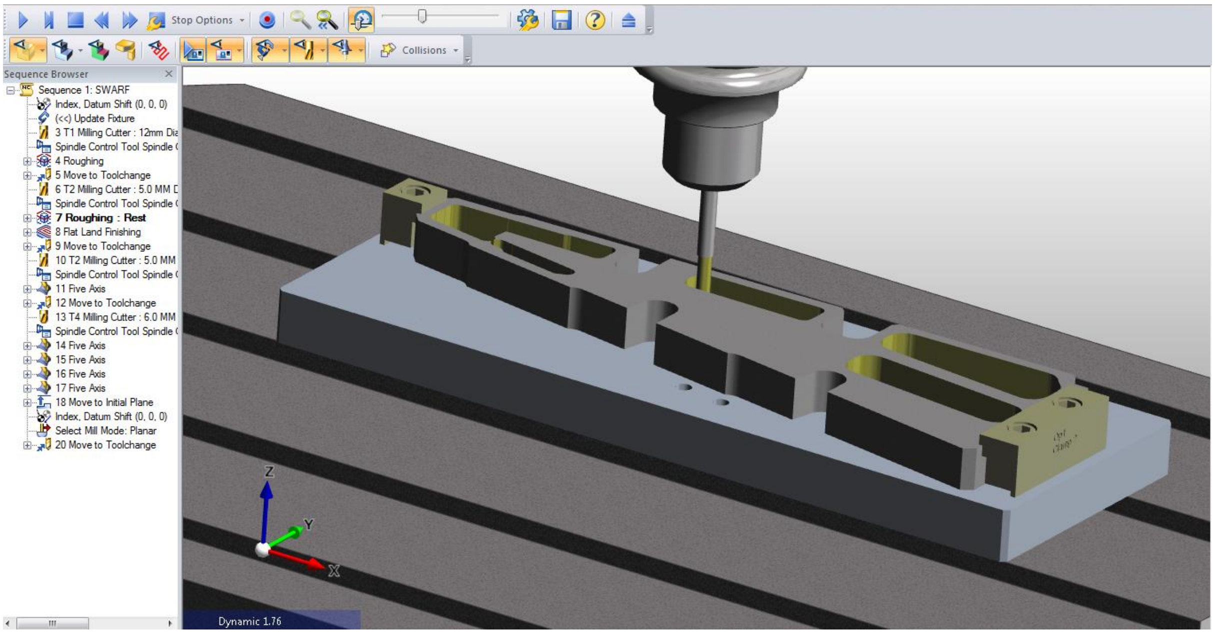
Figure 57: Design Model



Source: Figure retrieved from EdgeCAM software

Figure 58: Workpiece (Raw Material)

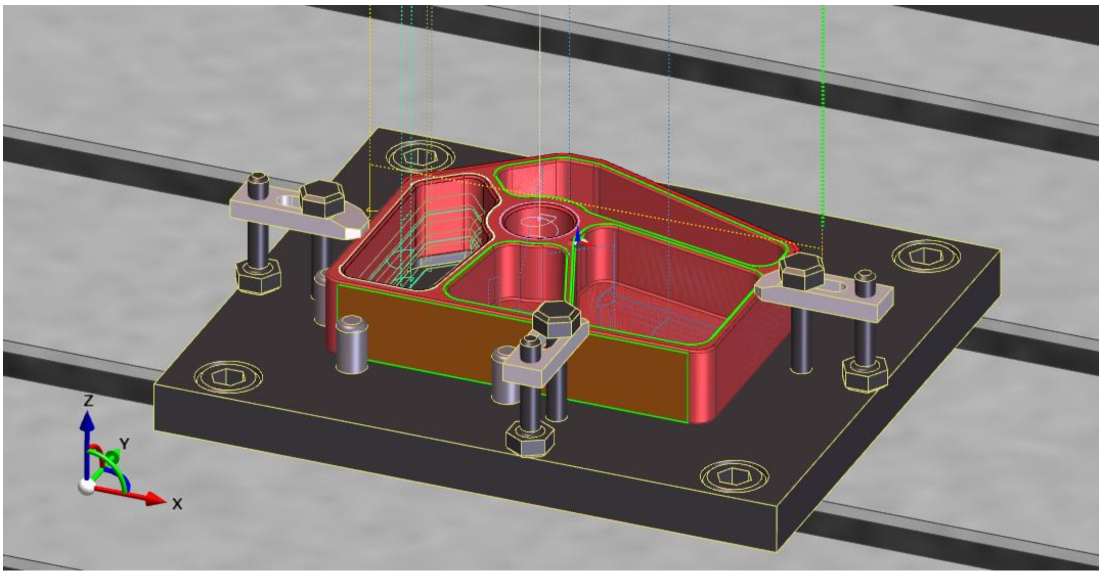
The design model and the workpiece are then assembled together to form the manufacturing model.



Source: Figure retrieved from EdgeCAM software

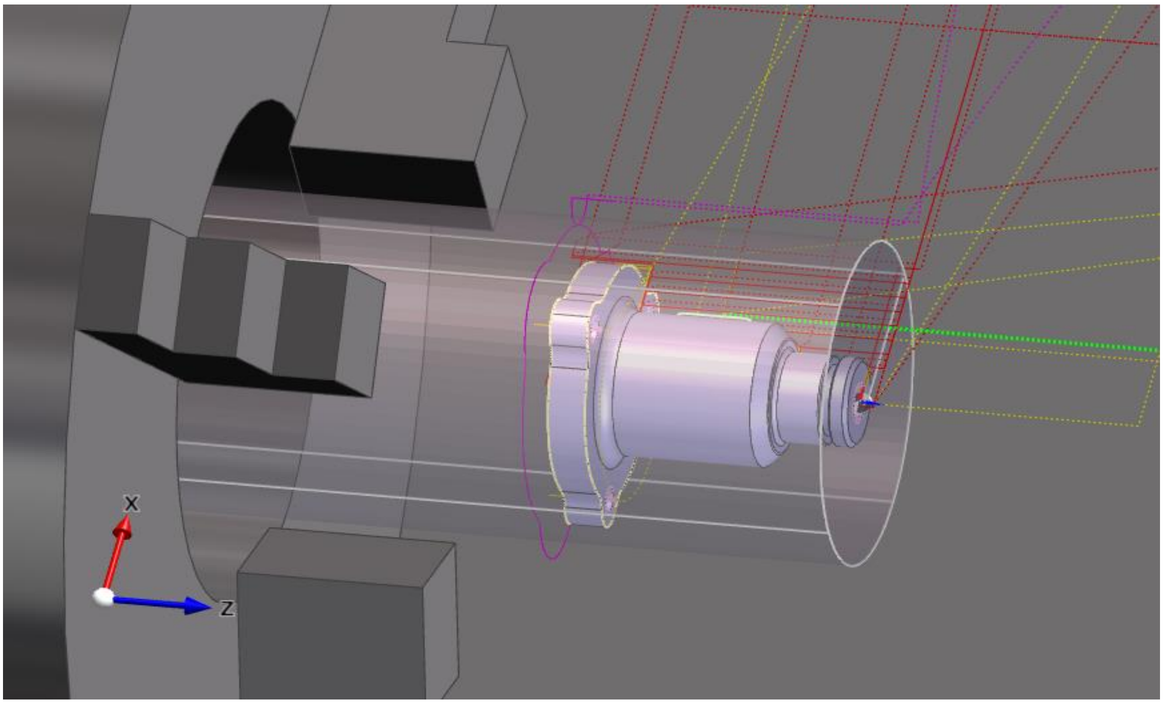
Figure 59: Manufacturing Model

Manufacturing operations are variable according to the operation executed. The milling operation is used for rough face milling or pocket milling operations and the axes are oriented by 3, 4, 5 or more axes. The turning operation is normally oriented in Z-axis and is usually collinear with the turning axis. Therefore, the turning cut is sketched in the XZ plane. A CAM software provides several facilities to create the profile.



Source: Figure retrieved from EdgeCAM software

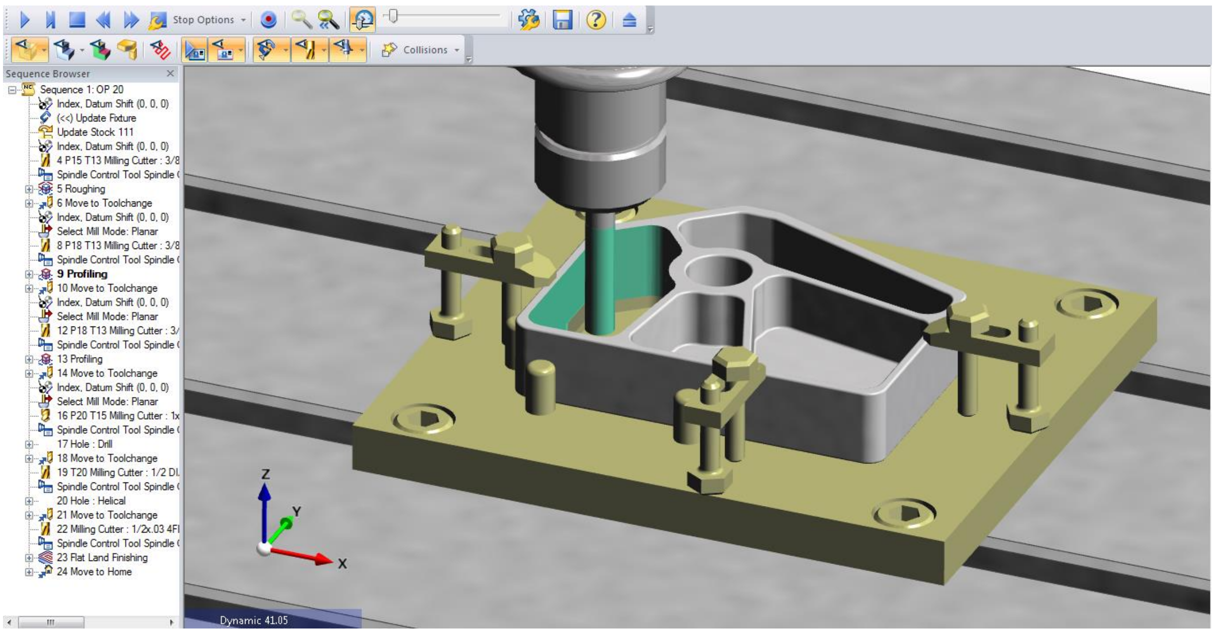
Figure 60: Milling for manufacturing operation



Source: Figure retrieved from EdgeCAM software

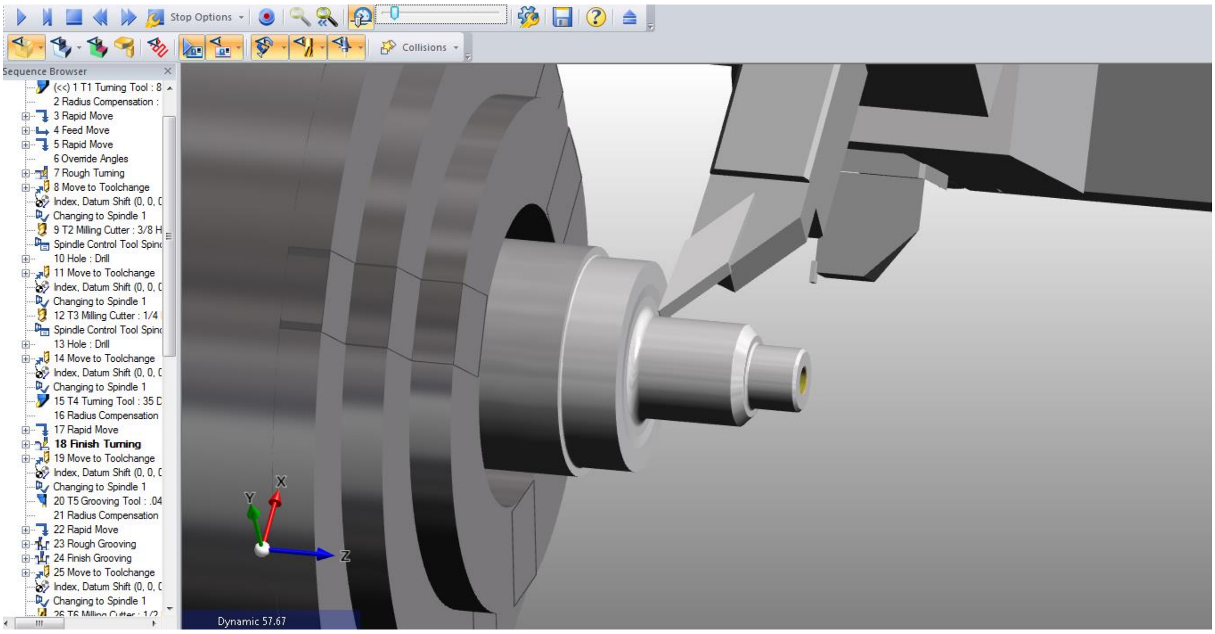
Figure 61: Turning for manufacturing operation

Through the manufacturing operations is often convenient to define the stock boundary and then create the NC sequences through the area clearance approach. For milling operation the sequences include drilling, reaming, boring, tapping, etc. However, for the turning operation the sequences include profile turning, groove turning, thread turning, etc.



Source: Figure retrieved from EdgeCAM software

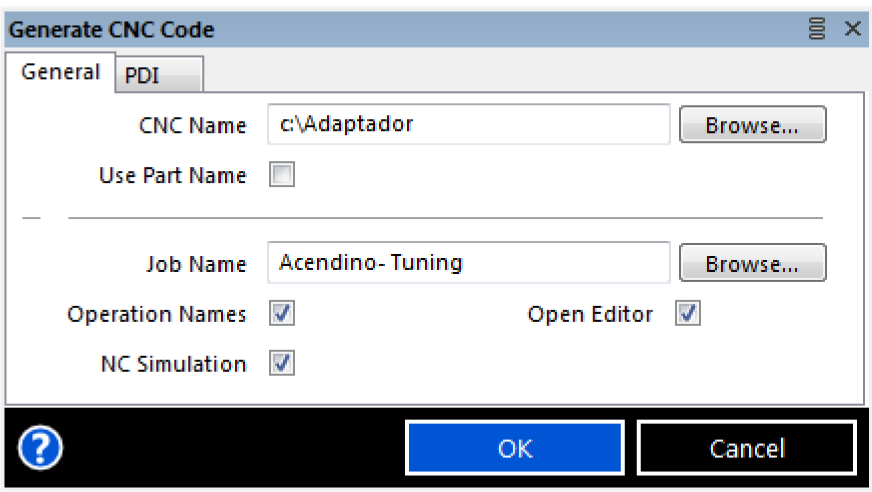
Figure 62: Milling sequences for manufacturing operation



Source: Figure retrieved from EdgeCAM software

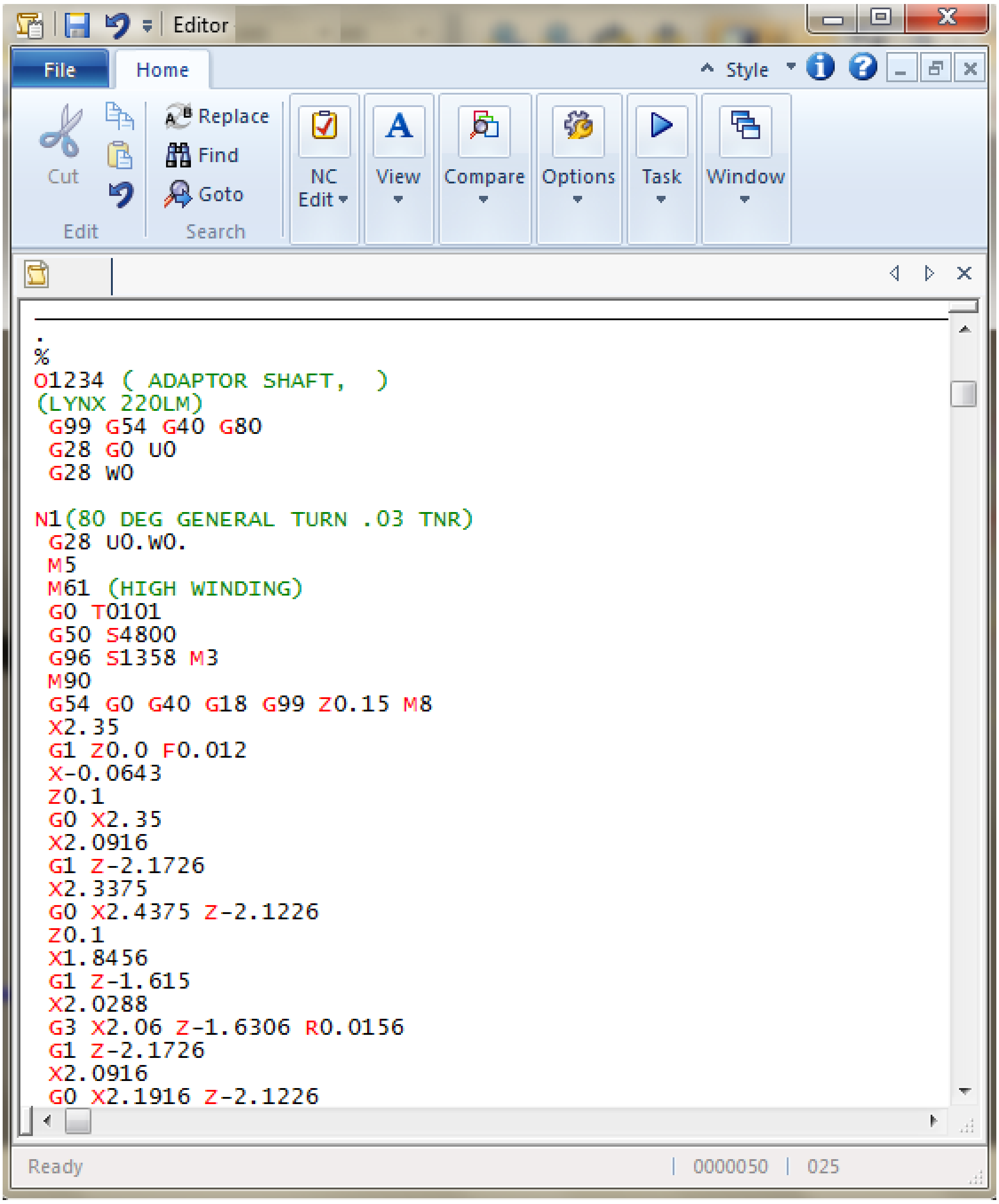
Figure 63: Turning sequences for manufacturing operation

Therefore the sequences operation could be transformed on a CNC program through the NC post-processing, and the NC program can be stored, listed or simulated on the screen for editing or modification if needed, or transferred to a CNC machine using DNC. The program could be seen, modified, compared and edited on a CAM editor.



Source: Figure retrieved from EdgeCAM software

Figure 64: NC post-processing, generate CNC code.



Source: Figure retrieved from EdgeCAM software

Figure 65: CAM editor.