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SENSING, SMART AND SUSTAINABLE PROCESS (S^3 PROCESS) DEVELOPMENT REFERENCE FRAMEWORK

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DANIEL CORTÉS SERRANO

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SENSING, SMART AND SUSTAINABLE PROCESS (S^3 PROCESS)
DEVELOPMENT REFERENCE FRAMEWORK

Declaration of Authorship

I, Daniel Cortés Serrano, declare that this dissertation titled, “Sensing, Smart and Sustainable Process (S^3 Process) Development Reference Framework” and the work presented in it are my own. I confirm that:

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- I have acknowledged all main sources of help.
- Where the dissertation is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Daniel Cortés Serrano

Mexico City, December 1st, 2021

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Dedication

To my mother, Margarita. For the immeasurable effort you have put in, the joy with which you show your love for your family and the energy in every step.

To my father, Juan Carlos. For the time, love, and dedication that you have put into each of the days since the beginning of our lives.

To my sister, Maggie. For your guidance, dedication, and example of overcoming.

To my brother, Ely. For every moment together full of joviality.

To my moon and stars, Paty. For your infinite patience, and love.

Sensing, Smart and Sustainable Process (S^3 Process) Development Reference Framework

By

Daniel Cortés Serrano

Abstract

Global challenges require efforts by nations to apply policies according to their situation and thus generate economic freedom. This concept is scalable to all units within the territory that create value. However, the reality of each nation is different; consequently, the policies that are implemented vary from region to region. Despite this, the vision of the industrial sector has opted for reproducibility and repeatability of operations, guaranteeing continuity and quality in the services and products offered. For this, it is necessary to integrate technologies, tools and communications infrastructure. This integration creates progressive development that benefits organizations and nations by meeting global challenges with the right policies. Ensuring the vision of these concepts involves analysis and investment in the different market alternatives. Therefore, it is necessary to characterize the production systems and define both automation and organizational objectives. In this work, the reference framework has been developed to include these objectives using the Sensing, Smart and Sustainable concept in the manufacturing processes of any firm. The contribution lies in how these steps are carried out, the analysis of the system, the reference model, the toolbox and the methodology to implement it in the design, redesign or characterization of the manufacturing process. In addition, 3 case studies are included in which its application is shown. The results of the research allow making long-term decisions about manufacturing processes.

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Abbreviations and Acronyms

Abridgement	Description
ANN	Artificial Neural Networks
AON	Artificial Organic Networks
AR	Augmented Reality
ATO	Assemble to Order
ATS	Assemble to Stock
BD	Big Data
BTO	Build to Order
C3	Citizen, Community and City
CAD	Computer-Aided Design
CC	Cloud Computing
CNC	Computer Numerical Control
CNN	Convolutional Neural Networks
CPS	Cyber-Physical Systems
CTO	Configure to Order
DFE	Design for the Environment
DL	Deep Learning
DPM	Development Partial Model
E3	Economy, Environment and Equity or Social
E7	Emerging Nations
ERP	Enterprise Resource Planning
ETO	Engineering to Order
GA	Genetic Algorithms
GDP	Gross Domestic Product
I4.0	Industry 4.0
ICT	Information and Communication Technology
IoT	Internet of Things
IIoT	Industrial Internet of Things
IMS	Integrated Manufacturing System
IMSy	Intelligent Manufacturing System
IPPMD	Integrated Product Process and Manufacturing-System Development
KDMP	Knowledge-Driven Manufacturing Process
LCA	Life-Cycle Assessment
MDP	Manufacturing Process Development
Micromachine	Reconfigurable Micro-Machine CNC Tool
MSME	Micro, Medium and Small size Enterprise
MTO	Make to Order
MTS	Make to Stock
NTP	Non-Traditional Processes
PMU	Phasor Measurement Unit
R3	Reduce, Reuse and Recycle

RF	Reference Framework
S^3	Sensing, Smart and Sustainable
S^4	Sensing, Smart, Sustainable and Social
S^3 Process	Sensing, Smart and Sustainable Manufacturing Process
SDG	Sustainable Development Goal
UN	United Nations
VR	Virtual Reality

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Chapter 1 Introduction

How to generate value and make countries grow has been a question that has been around for a few decades. The great nations proposed economic support to the developing countries. However, this did not improve the situation, and on the contrary, it generated a deficit in the growth of the nations. The case analysis was conclusive; the need is imperative for a country to promote its growth and regulations that can be applied to encourage development. This concept is known as economic freedom, and it is the primary facilitator of economic development in nations (Scott, 1997). Economic freedom is not exclusive to governments but scalable to each of the organizations that make it up and generate growth within the territory. Therefore, this principle could be applied to industrial sectors that allow progressive development.

Due to the progressive development, it is not strange to try to cover the global challenges from the industrial sector in which some firm is located. Since the beginning of the 21st century, global challenges have focused on reducing poverty, developing technology to provide a better quality of life, reducing crime, accelerating scientific advances, developing sensitive long-term policies, increasing shared values, gender equality and reverse the deterioration of climate change (Glenn, Gordon, & Florescu, 1997). These challenges could be summarized into five groups: i) Economics, ii) Environment, iii) Geopolitics, iv) Society, and v) Technology (World Economic Forum, 2020). The goals of these initiatives are to shorten the gap in social strata (Agenda Pública, 2020), to address sustainable production and consumption (D. Mishra, Gunasekaran, Papadopoulos, & Hazen, 2017), to improve the overall governance and efficiency system (Madinah & Bwengye, 2018), to seek greater well-being and collaboration in world society (United Nations, 2020), that has become global, with the respect that everyone deserves (United Nations, 2015) and, to increase cyber security making use of technological advances in the different productive activities of nations (OECD, 2018). The proposed objectives are not exclusive to a sector but joint actions that allow the simultaneous development of operations in each area.

The challenges seek to be covered by government policies in conjunction with the productive sectors of the nations. Among them, secondary or industrial services stand out. In the world, this sector represents 30% on average of the Gross Domestic Product (GDP) (Central Intelligence Agency, 2017) and 23.01% of the employment worldwide (The World Bank, 2020). This percentage increases in developing countries. Therefore, the commitment of the new generations should focus on generating progressive development in industrial sector establishments since they create jobs and allow the development of the surrounding regions.

At first glance, the industrial sector refers to the processes that must be carried out to transform raw materials. This fact has generated knowledge and applications in various fields, gradually tackling the challenges above. However, the initiatives that covered all of them fell short in terms of focus and scope. Even with this, concepts and initiatives emerged that promote a top-down or bottom-up mindset to address the various challenges of the industry. The emerging ideas bring together technologies, concepts, communications, security and different engineering areas that promote the automation of systems for effective decision making within manufacturing firms. The industry's series of guidelines, industrial objectives, desired scopes and activities are known by the concept of Industry 4.0, which has been highly accepted within the industrial sector (Dalenogare, Benitez, Ayala, & Frank, 2018). Novel articles are centred on describing the impact of adopting these technologies that comprise it (J. M. Müller & Voigt, 2018).

On the other hand, Micro, Small and Medium Size Enterprises (MSMEs) still represent the working force capacity of developing countries. The main advantages offered in these manufacturing firms are the flexibility of their production lines (Cronin, Conway, & Walsh, 2019) and the fast response to introduce novel products (Ferreras-Méndez, Olmos-Peñuela, Salas-Vallina, & Alegre, 2021). There are some critical gaps in MSMEs that thwart their development. Recurring problems for developing enterprises are mainly due to the lack of knowledge of their internal and external environment, their position in the marketplace and their fragile structure to expand operations. Besides, due to the high interaction with increasingly affordable technologies, companies orient strategies to digitization, abusing information and communication technologies. However, this has an effect contrary to that expected on multiple occasions because they neglect what generates value in their business and focus on using technological tools.

Even the company environment favours the use of technology-based tools to know the status of the business in real-time; it is just as essential to create collaborative networks, be aware of the environment, identify the generation of value in the products offered and adequately structure the processes and systems that allow its elaboration, though. Thus, opportunity areas for enterprises could be grouped in the lack of five competencies: i) structured processes, ii) industrial environmental knowledge, iii) inventory control, iv) technological adoption or reluctance to change and v) accounting and finance.

The principles of automation mainly cover the identified areas of opportunity (K. L. S. Sharma, 2017). Hence, it is intended that there is knowledge of the internal and external environment that allows the optimization of production (ii), the inventory maintains optimal levels to ensure production maintaining a certain level of quality (iii), the adoption of technology focused on productivity (iv). All these principles also consider that the process is cost-effective and structured to cover accounting issues and keep the company's finances healthy. Seeking automation in developing companies represents considerable efforts in resources, facilities, workforce training, supply chain, and other unaffordable factors for manufacturing firms. However, a properly structured process establishes the steps to be followed within the organization and the resources necessary for its implementation, whether it is an organizational or manufacturing process.

In recent years, by decomposing the functions that automation fulfils, the concepts of Sensing and Smart have been reached to develop the necessary tasks within a productive system, and the vision of Sustainability has been introduced as a third axis (Chavarría-Barrientos, Camarinha-Matos, & Molina, 2017). The Sensing, Smart and Sustainable (S^3) concept seeks to address the functions of automation as a stepped process that can be adapted to any system and entity. Thus, a system that adopts S^3 solutions provides integral entities which respond effectively to current market demands. The S^3 concept appeared as a reference framework for sustainability, viability, validity and maintainability in broad economic, social and environmental terms.

It is a concept that, although it could be used in any industrial context, is especially useful to start the automation of manufacturing firms in a structured way. And the concept does not cover only the management of operations or services because it follows the trends of a bottom-up mindset. It also allows characterizing products, manufacturing systems, business units, digital models, organizational and manufacturing processes. Although administrative and manufacturing processes could be studied similarly, only the latter will be reviewed to delve into solutions to this issue during this dissertation.

Throughout this work, the S^3 Manufacturing Process concept will be delved. This concept makes use of the intrinsic characteristics of each of its components in a manufacturing process. Sensing refers to a system's capability to detect events, acquire data, and measure changes that occur in a physical environment. Smart incorporates data processing, actuation, control and sharing functionalities to make decisions in a predictive or adaptive manner. Sustainability is related to the design process, either ethical, operational or robust. It aims for environmental, social or economic terms.

However, in more recent studies about the products, processes and manufacturing system development, a fourth axis has been incorporated that places the human being as the primary focus during their design, creation and start-up. This attribute was named Social; it represents the future work of this research. Although it will be described broadly within the concepts for the manufacturing processes, it will not be the central axis of this research. However, the precedent will be left so that the investigation continues. In the creation of products, its role is clear, which is why this fourth axis emerged; however, for the manufacturing processes and system, its position must still be glimpsed. Its study will be multidimensional due to the role that a social being plays in these entities.

The S^3 and S^4 definitions will be described in the following chapters. Only the former would be delved and integrated for the characterization, purpose, and improvement in manufacturing processes due to their importance for any manufacturing. The S^3 Manufacturing Process will be described throughout this work. A reference framework, a methodology, a toolbox and the implementation for the development or updating of manufacturing processes are presented. In addition, this work aims to serve as a reference for manufacturing firms but does not limit its use to them. The S^3 concept seeks automation as a strategy understood in turn from a sustainable point of view, so its implementation or description of entities goes further.

1.1 Manufacturing design overview

S^3 Manufacturing Process Reference Framework proposes initiatives that can positively influence the economic and professional development of society. Therefore, the development of manufacturing processes is used as a strategy to support economic and professional development. The manufacturing and educational sectors play a crucial role in generating knowledge, offering professional development and adding value to existing enterprises. The primary motivation that prompted the development of this thesis is based on the fact that it provides a substantial impact on structuring manufacturing processes. The reference framework aims to be used for manufacturing organizations, considering technology adoption as a pillar of progressive development, stretching the gap about the challenges that enterprises may overcome.

In order to understand the motivation of this research, it is necessary to turn to the literature and observe the current state of the art about manufacturing design, including i) product, ii) process, iii) manufacturing system and iv) business process. The search for these terms was carried out within the Scopus and Web of Science databases. Table 1-1 shows the number of articles that correspond to the terms above.

Table 1-1 Manufacturing design overview

	Product design	**Process design**	**Manufacturing system design**	**Business process design**
Scopus				
Total	**92,282**	**33,171**	**669**	**444**
2019-2020	9,110	3,220	15	39
Percentage (2019-2020)	9.87%	9.71%	2.24%	8.78%
Main area	Engineering	Engineering	Engineering	Computer science
Web of Science				
Total	**15,150**	**13,620**	**344**	**211**
2019-2020	1,602	1,780	27	13
Percentage (2019-2020)	10.57%	13.07%	7.85%	6.16%
Main area	Engineering manufacturing	Engineering chemical	Engineering manufacturing	Computer science information systems

Besides, it offers the articles that fit from 2019 to 2020, the percentage these have had of the total and the foremost field in which the publications are located. The importance of recent publications implies the progress that has occurred in the area. Manufacturing firms have shown interest in advancing with universities and government policies to cover these fields progressively (Lee, Lee, & Shon, 2020). For its part, product design is a consolidated field with a presence in multiple engineering disciplines and particularly manufacturing. However, the other three terms that are related to manufacturing design are still growing.

The fields in which the design of processes, manufacturing systems and business processes are located are still growing. For these terms, no guide allows their development in the manufacturing field (more details are provided in Chapter 3). This is why most processes and manufacturing systems are based on product design in the industrial sector; however, this entails challenges to create a solid and comprehensive structure in the long term.

Issues related to manufacturing design are presented in Figure 1-1. The topics show a relationship in a scientometric way. Among the most current themes are additive manufacturing techniques, 3D design applications, methodologies, new industrial research and automation derived from the set of computational resources, designs and methods. This search shows current trends and, therefore, interest in the development of these topics.

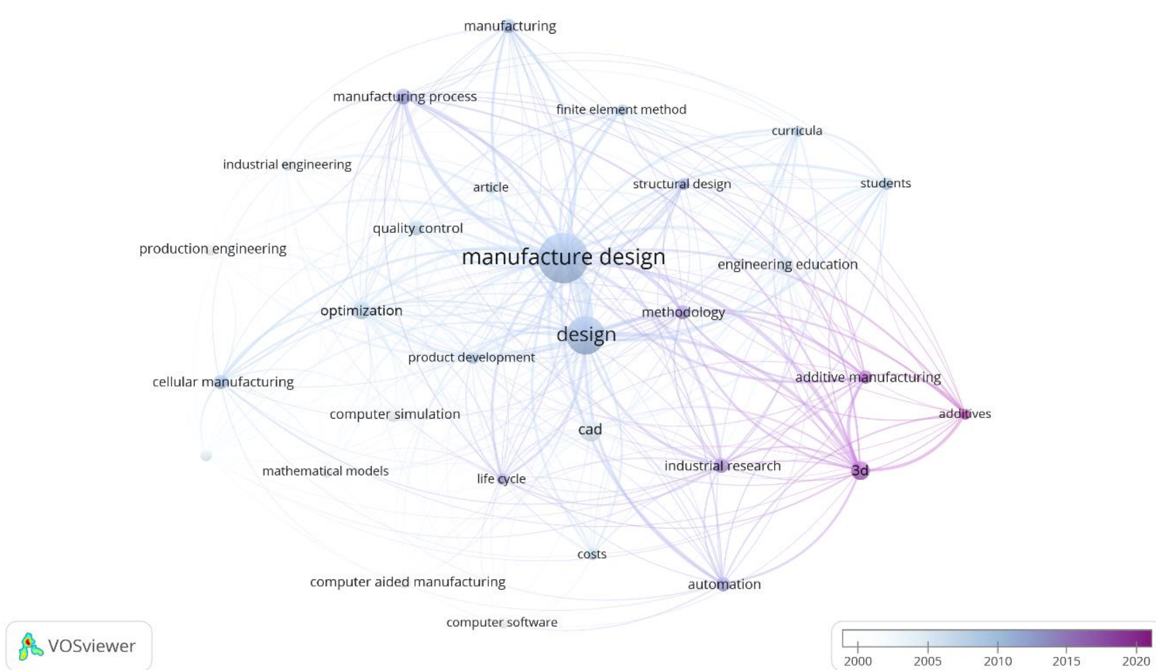


Figure 1-1 Manufacturing design overview. Own elaboration map in VOSviewer

Manufacturing design implies the conjunction of engineering activities to develop solutions in a structured way. It is usual to find the conjunction of methodologies, techniques, training and tools as part of the training required by those who will carry out design tasks. To this trend observed in manufacturing design, multidisciplinary knowledge could be added to seek unconventional solutions in particular projects. Figure 1-2 shows trending topics about manufacturing design.

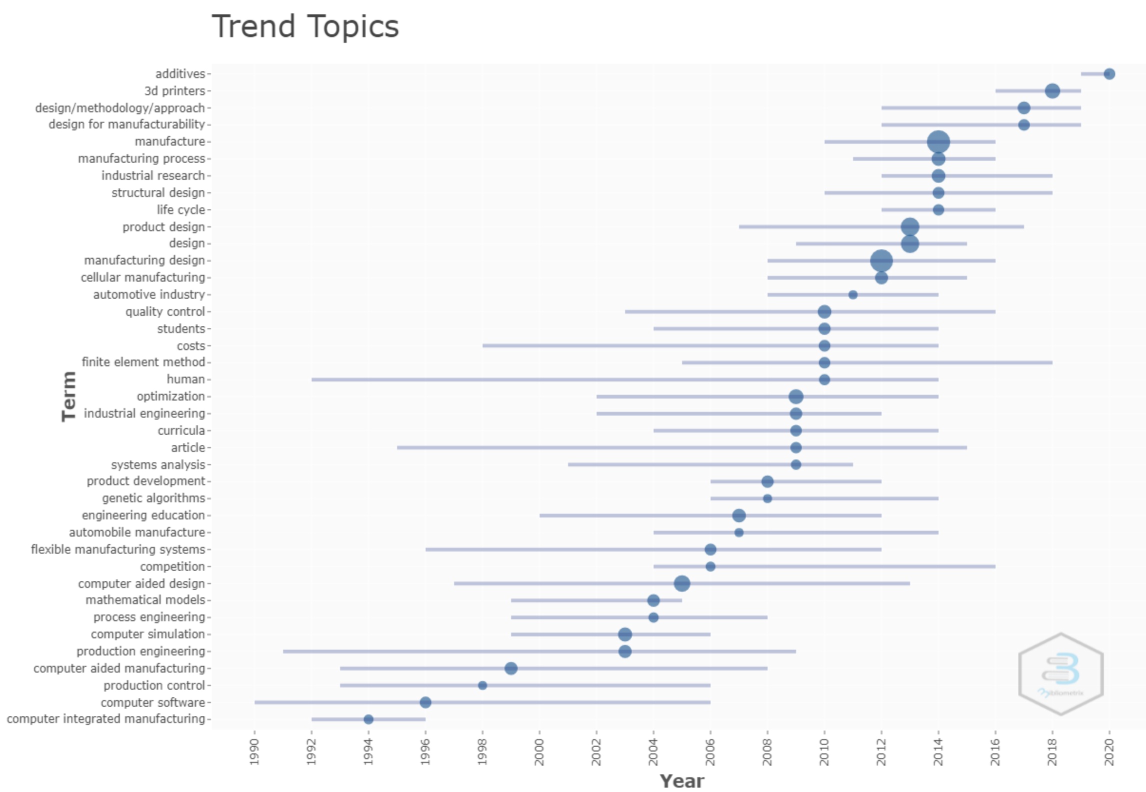


Figure 1-2 Manufacturing design trends. Own elaboration map using Bibliometrix.

Within the topic of manufacturing design, manufacturing processes are essential to the progressive development of manufacturing firms. In this way, manufacturing processes correspond to the crucial way in which an organization generates value. These practices are scarce in the literature due to the multidimensionality of the subject, how broad it is to condense it, and the multidisciplinary knowledge required to carry out the development of manufacturing processes.

Furthermore, these techniques are usually protected for exploitation by particular business units. The methodologies for the development of processes could seem evident for the process to be developed; however, they constitute an area of opportunity that can be exploited by large manufacturing firms and micro, small and medium business units. In essence, it is the core piece that can lead to the progressive development of an organization and, consequently, of nations. In recent years, there has been a special interest from various nations and manufacturing firms in research on the design of manufacturing processes. Figure 1-3 shows the increase in publications by nation.

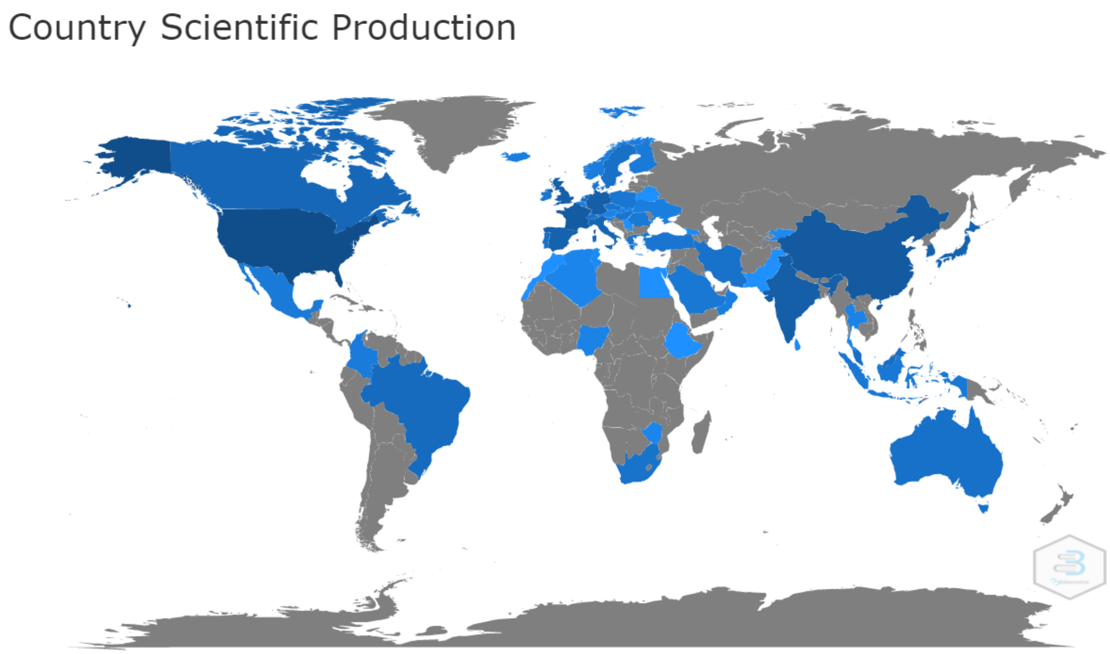


Figure 1-3 Country scientific production of manufacturing design articles. Own elaboration map using Bibliometrix.

In the literature, these topics are traceable for a couple of decades, however, a rebound of publication has been observed for five years. Therefore, the scarcity of this key knowledge for an organization is delved as a methodology for its development and adoption. Its importance lies in the structure that grants the automation of processes that allows the growth and development of companies. Not only is investment required by organizations for research on these issues, although these are the ones who promote research in various areas of interest, nations benefit from this interaction, and those who carry out scientific development are research institutes, universities, or affiliated centres. In Figure 1-4 the main exponents in terms of manufacturing design, the main keywords and the recurring themes of the articles are presented.

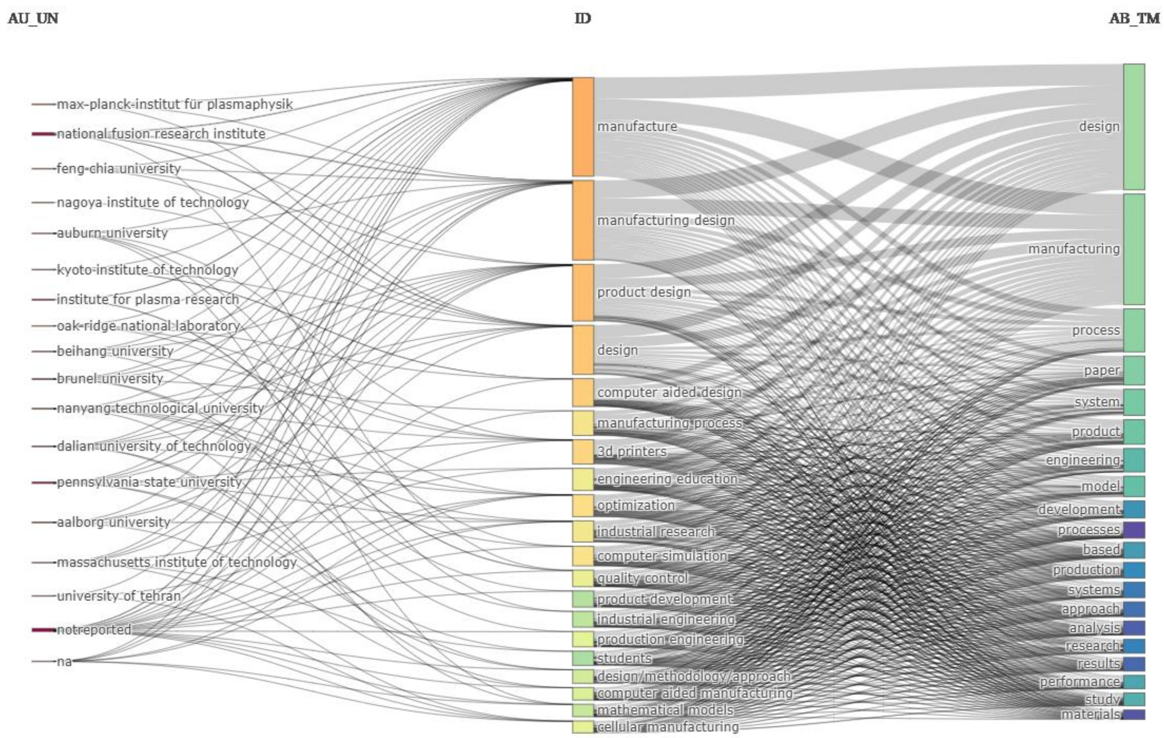


Figure 1-4 Affiliation scientific production and relevant topics of manufacturing design. Own elaboration map using Bibliometrix.

1.2 Justification

Manufacturing firms were born in the middle of the XVIII century; their goal was impulsed by society's needs, thus bringing essential resources closer to minimize transportation (Krugman, 1991). Over the years, these needs were met by creating new organizations, driven by demand or by creating specific consumer niches (Dobrev, Kim, & Carroll, 2002). The relationship between manufacturing companies and society is based on the laws of supply and demand that have driven the creation of ever-expanding markets of all kinds (Lillo, Mike, & Farmer, 2005). This has resulted in consumption structures in the world with the essence of offering a good or service at the market's price.

Manufacturing firms have worked in this way since their inception (Bates, 2007). New forms of production have been discovered, more efficient techniques, methodologies to introduce products, logistics, sales and marketing strategies (Gustavsen, 2003). However, they continue to constitute traditional supply and demand systems based on market speculation (Yu, Chen, & Liang, 2021). There is extraordinary evidence that this system works, as it has withstood the passage of two centuries (Vollmann, 2005). However, the new ideological currents of consumption and openness of knowledge have made the market demand a new relationship (Kartajaya, Kotler, & Hooi, 2019).

The primary motivation for migrating from a traditional system was the productive capacity offered by a firm, market demand and the guarantee of delivering a product to the consumer that would meet their needs (Calà et al., 2017). Despite the desire to cover more markets and diversify available products, this was not achieved until mass production in the late XIX century, which allowed producers outstanding production, lower costs and more regional coverage (Roser, 2016). Despite this, it was not until the marketing departments listened to the customer and end-user about their needs and preferences that products began to be designed to meet specific needs in the population (Duray, 2002). Even so, it still lagged behind current manufacturing trends. Advances in the middle of the XX century allowed the design of lines with the capacity for product diversification and the semi-automation of production lines with the adoption of monitoring and control systems in the industrial environment (Kumar, Subramaniam, Husin, Yusop, & Hamidon, 2007). It was deduced that the development of technologies and communications were not enough individually to increase the value in an organization, but their integration and take advantage of the production, process and sharing of data to achieve automation objectives and thus increase the production of the systems (Gacek, Geynisman, Proudfoot, & Minnick, 2001). This has generated an impact in communicating infrastructure, interaction with other companies and listening to clients (Li, Su, & Henshall, 2004). Allowing to manage the sequence of activities, be aware of the environment, and make more efficient decisions in any field (Skitka, Mosier, & Burdick, 1999).

In fact, the manufacturing systems have become more self-sufficient when being operated and capture information from the environment and be aware of the parameters required to be measured through sensors (Bi & Kang, 2014). They have been equipped with intelligent features to process information, perform routines and communicate with another system or with the workforce certain information (Asche, 2016). Nonetheless, these increasingly complete systems require a sustainable approach during their development, operation, and end of life to complete a cycle (Bhamra & Lofthouse, 2016). The world's resources are finite, while the impact on society and the environment are a real issue for this generation and those to come.

The manufacturing systems of the last decade have been driven by integrating the pillars that incorporate skills, technologies, methodologies, training, adaptation, rational use of resources and automation at the time operating; this set of concepts has been called Industry 4.0. (I4.0) (J. Müller & Voigt, 2017). However, as I4.0 is a concept, various interpretations have been generated from it, taking the available resources and using the characteristics found by each of the individuals. The full implementation of these resources is far from the approaches that organizations have made (Cañas, Mula, Díaz-Madroñero, & Campuzano-Bolarín, 2021). It requires multidisciplinarity to carry it out, investment in resources and the priorities of the organizations. The implementation of this integration has needed the perspective of enablers, whether they are methodologies, approaches, regulations or success stories that contribute to the migration process from a traditional manufacturing system to one that takes advantage of information to increase value of the organization (Machado et al., 2019).

In this sense, the S^3 concept works as an enabler to arrive at the I4.0 vision. The concept aims to characterize the attributes of a system in solutions for both automation and sustainability. Any system can be analyzed with the Sensing, Smart and Sustainable attributes (Chavarría-Barrientos et al., 2017). These refer to the ability to detect variations, the ability to process and share information, and sustainable objectives measured in three dimensions. The purpose of this concept lies in the characterization to identify areas of opportunity in the analyzed systems. The S^3 concept can be used for the characterization, design or redesign of systems, however, its implementation must be carried out specifically for manufacturing entities. The attributes that comprise an S^3 system are shown in Figure 1-5.

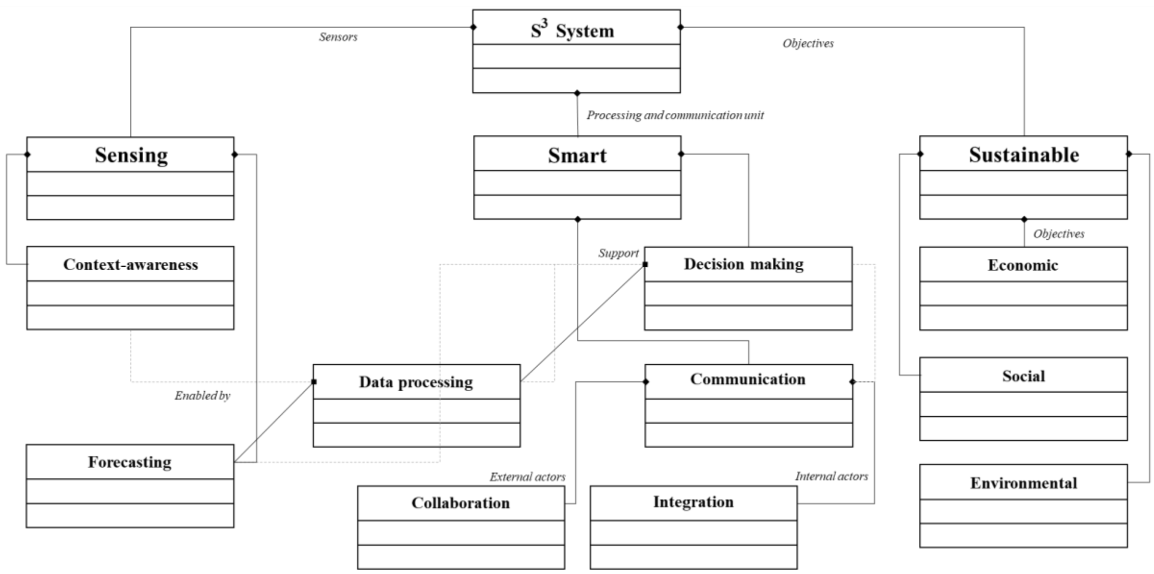


Figure 1-5 S^3 System unified model language diagram.

As the concept matured, a fourth attribute of the system was introduced. The intention of creating designs centred on the human being, Social, this system has the relationships presented in Figure 1-6. This fourth attribute will not be described throughout the chapters; however, the study of the S^3 concept and its applications have been extended to the S^4 concept at the time of publication of this work. Future researchers are encouraged to continue with this work, and hopefully, the scheme serves as a guide to that end.

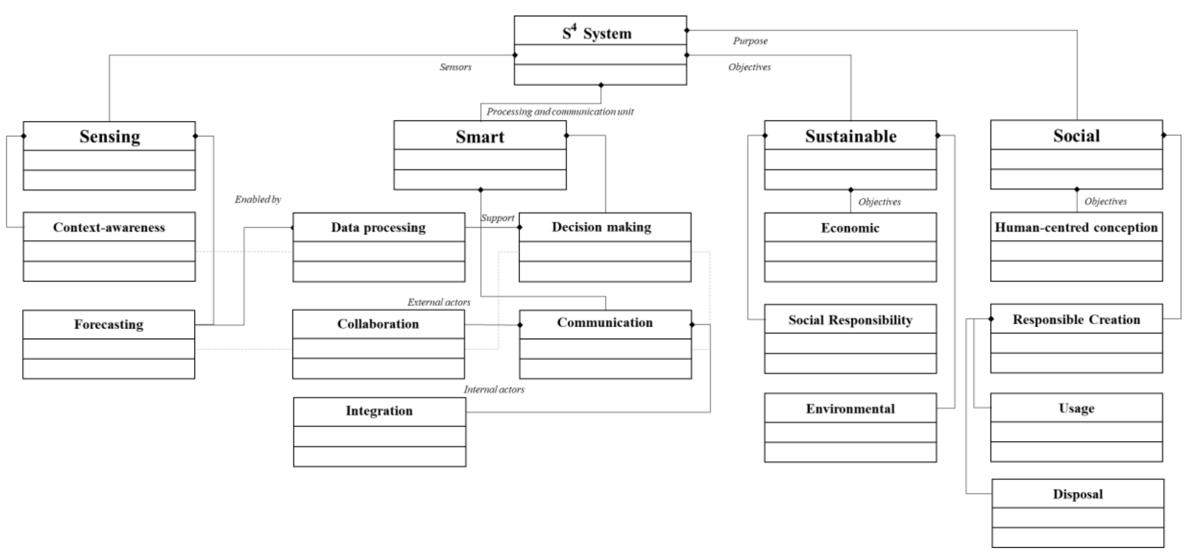


Figure 1-6 S^4 System unified model language diagram.

An S^3 system consists of three fundamental characteristics, Sensing, Smart and Sustainable. Sensing is achieved through sensors or sensor networks that allow collecting information about the environment, operation and post-processing of activities, enabling the system to be context-awareness. Smart is conceived by those attributes that will enable carrying out tasks that involve information processing, communication with other systems and decision-making. Information processing is required to make forecasts that allow predicting situations of various kinds. Also, communications are not limited to previous or subsequent entities, but to exchanging and sharing information between internal and external agents, between subsystems and humans. Finally, decision-making is based on the information available, predicted and communicated to pursue a given objective. The Sustainable attribute impact the long-term capabilities of an organization to survive and prosper while taking into account its economic, environmental and social performance. These objectives can be observed from the system's conception since the decisions made throughout the design, operation and end of its life cycle must be aligned with the organizational objectives. The economic aspect includes the need for an organization to maintain operations, for this, the profitability of its product or service can be affected by this attribute, as well as its medium and long-term planning to grow its operations and increase the jobs generated. The social aspect from the sustainability attribute refers to the actions that a manufacturing firm allocates in favor of society. Be it its workforce, the community in which it operates, the territory in which it is located or a perceived impact for its clients beyond the offer of the good. The environmental aspect refers to the responsible use of materials, services or consumables, actions to reverse the change caused by the system and the renewal of environmental resources. The Social attribute must not be confused with the social aspect of an organization. The Social attribute is understood as an integral solution that places the human being as the leading actor of the entity to be developed. In other words, it seeks to enhance functionality, customization, use, and disposition without losing sight of the responsible creation of entities to satisfy user needs. In addition, it understands the citizen environment and places the solution with a comprehensive and human-centred aspect throughout the supply chain.

Considering the S^3 concept, any system can be characterized with Sensing, Smart and Sustainable attributes. Therefore, the entities that comprise manufacturing firms can be characterized in the same way. The main entities are Products, Processes and Manufacturing Systems. Therefore, if these entities are seen as a system, it is possible to identify a certain level of automation in three categories from a design point of view. Therefore, once its characteristics have been identified, it is possible to i) exploit the strengths of the entity for economic, social or environmental goals, ii) design more automated entities considering the sustainable impact from its conception or iii) redesign the entities with the aim to strengthen their attributes and consequently, to upgrade a level in its attributes or automation.

In the case of this dissertation, a system will be understood as a Manufacturing Process entity. Therefore, by breaking down a manufacturing process into subsystems, it is possible to identify the following. Machinery is, in fact, the first level of complexity inside a manufacturing firm while producing goods. Machinery is understood as the physical machine that performs repetitive labour that the human workforce did previously. However, machinery requires information, raw material, auxiliary services and driving force to accomplish its objective. Workstations represent the second level of complexity in manufacturing. Then, gathering multiple stations, it is obtained a cell of manufacturing comprised of stations that produce similar goods, thus minimising time and waste. Moreover, the conjunction of cells forms the shop floor of a manufacturing firm, which comprises information, cells, people, raw material, and sometimes it includes a retail sale. Finally, the fifth level of complexity inside a manufacturing firm is the factory. Factories are the physical areas where the production of goods occur. They are comprised of machinery, workstations, manufacturing cells and shop floor.

For the contribution of this work, the manufacturing process is included as a single entity, an analysis will be carried out on it, and a reference framework will be generated with at least the following applications i) Design manufacturing processes with S^3 solutions based on a product, ii) Characterise existing manufacturing processes and improve their S3 attributes, and iii) Selection of S3 solutions in manufacturing processes. For this, the challenges that exist at the levels previously described have been studied to understand the current situation in the design of manufacturing processes.

Challenges of manufacturing have been addressed over the years at different levels of complexity which are related to the following aspects (Silva, Ablanedo-Rosas, & Rossetto, 2019)(Kazemi, Modak, & Govindan, 2019):

- Creation
  - Design. From idea to the start-up of the system. It includes aspects of functional design, description of its components, description of its performance in a set of procedures and the implementation to contribute to the objective of the manufacturing firm. (Hill, 2000)(Sinnwell, Krenkel, & Aurich, 2019) (Rehg & Kraebber, 2012).
  - Planning. Considering supply chain management, needed resources, services and cohesion between subsystems, all steps, information and activities should be stated and validated among departments. Understanding the manufacturing process is crucial while planning the activities or redesigning what has been implemented before. (Hees et al., 2017; Hees & Reinhart, 2015; Hong, Chu, & Yu, 2016) (Dotoli, Fay, Miśkowicz, & Seatzu, 2019).
  - Security and Safety. Security must be planned in different aspects before production starts. It should assure the safety of the workforce in each system and a protected channel of communication among collaborators. Related with physical components of parts produced, emissions from processing material, ergonomics, information treatment and cybersecurity. (Jeong, Lee, & Lim, 2019; Wells, Camelio, Williams, & White, 2014).
  - Cost. Even it is the primary concern of manufacturing firms; the cost is comprised of every single activity that occurs in every level of complexity of the organisation and administration activities. It is linked with manufacturing resources during the functioning stage; however, it must be estimated based on historical information available during the creation stage. Common subjects to be optimised are i) process, ii) material, iii) workforce productivity and iv) inventory. (Fisher et al., 2018; Moser, Isaksson, & Seifert, 2017; Zaman, Rivette, Siadat, & Mousavi, 2018)(Rawat, Gupta, & Juneja, 2018).
- Functioning
  - Quality. It is referred to what customers and clients perceive from the manufactured goods. Internal and external customer's perspective is required when improving daily operations. It requires a multidisciplinary perspective, equipment capacity, mapping processes, and where to implement quality

controls. (Colledani, Tolio, & Yemane, 2018; Dhafr, Ahmad, Burgess, & Canagassababady, 2006)(Rezaei-Malek, Mohammadi, Dantan, Siadat, & Tavakkoli-Moghaddam, 2019)(Zennaro, Finco, Battini, & Persona, 2019).

  - Production planning. Effective implementation of manufacturing processes, considering load, processing time, efficiency in previous and subsequent operations and discharge of materials for the following processes. It includes schedulling, master production planning, aggregate planning, and long-term capacity planning. (Akbar & Irohara, 2018; Caggiano, Bruno, & Teti, 2015; Hu, Zhu, Zhang, Lui, & Wang, 2019) (Gunasekaran et al., 2019).
  - Resources. Practical usage of available resources that organisation has included workforce, machinery and cash flow for materials purchase, payroll and production capacity expansion investments. Nonetheless, for this work, resources will be limited to the study of the following requirements: processing material and waste, auxiliary services (e.g. coolers, heat exchangers, inert transport gases), energy supply and emissions. In Chapter 3 this will be detailed. These are the opportunity areas to optimise during the functioning of subsystems. (Papetti, Menghi, Di Domizio, Germani, & Marconi, 2019; Puik, Telgen, van Moergestel, & Ceglarek, 2017)(Groover, 2007) (Shen, Choi, & Minner, 2019).
- End of life
  - Disposal. When components of the factories reach the end of their life, they must be correctly deposed to diminish the environmental impact of their parts. However, the deposition must be planned and considered in the early phases of the design to decrease long-term costs. (Harmer, Cooper, Fisher, Salvia, & Barr, 2019)(D'Amato, Mazzanti, Nicolli, & Zoli, 2018; Das, Rukhsana, & Chatterjee, 2019) (Eslami, Dassisti, Lezoche, & Panetto, 2019).

Table 1-2 presents the challenges that face manufacturing in different levels of complexity. In the manufacturing sector, emergent technologies must be used to provide a solution to the obstacles exposed. Manufacturing firms nowadays must pursue reconfigurability, modularity, decentralisation, real-time communication with the supply chain, but above all else, to produce based on knowledge information, taking advantage of data processing technologies. Optimising these aspects should create a better mapping of activities, considering the information required to deliver effectively. All in all, emergent technologies could be used to optimise daily production and solve existing challenges that the manufacturing sector faces.

There are observed some critical gaps in MSMEs that thwart their development. Opportunity areas could be grouped in the lack of five competencies. i) Structured processes, ii) industrial environmental knowledge, iii) inventory control, iv) technological adoption or reluctance to change and v) accounting and finance (Crane, 2020). Thus, new industrial practices aim at covering these lacks industrial competencies.

The challenges that manufacturing faces to migrate from traditional to Intelligent Manufacturing System (IMSy) involve the creation, operation and end-of-life of the manufacturing entities that are developed in them. Furhtermore, contrasting these challenges with the critical gaps faced by MSMEs, areas of opportunity are identified in the following subjects i) methodologies and specific activities for the development of manufacturing entities, ii) characterization of critical variables of the processes, iii) selection of tools for the implementation of the design, iv) adoption of technology according to organizational objectives and v) evaluation of technologies that allow increasing production.

Together with the new trends in the design of entities, these manufacturing challenges have resulted in the conjunction of the S^3 concept as an enabler to decompose the traditional manufacturing processes in their levels of each of their attributes. With this, once its characteristics have been identified, it is possible to carry out an individual update of its components to increase its level of automation according to the objective set by the manufacturing firm. In this way, the cost of trying to automate the entire production system is reduced, but the updated attributes will match the organisation's long-term objectives.

The steps described above could not be found in the literature review and constitute a fundamental link for updating the manufacturing systems. This framework is helpful in any organization, and the attributes presented in the S^3 concept are embedded in any manufacturing process. The development of the reference framework discussed in this work aims to stretch the gap and transition between traditional manufacturing into IMSy.

Table 1-2 Challenges of manufacturing at different levels. Creation, execution and end of life

	Creation				Execution			End of life
Level	Design	Planning	Security	Cost	Quality	Production planning	Resources	Disposition
Machinery	▪ Adaptability ▪ Tools ▪ Standard components	▪ Selection of machines	▪ Ergonomics ▪ Use manual ▪ Emergency stops ▪ Indicators ▪ Use requirements	▪ Material ▪ Maintenance ▪ Transportation ▪ Dispensable	▪ Sampling methods of raw material	▪ Time flexibility ▪ Time distribution	▪ Information updating ▪ Information asymmetry	▪ Disassembly of parts ▪ Management of scrap
Workstation	▪ Network design	▪ Skills and knowledge of workforce ▪ Flexibility to lot sizing	▪ Ergonomics ▪ Distributed and decentralised control	▪ Services ▪ Material ▪ Safety equipment	▪ Inspection of raw material	▪ System Dynamics	▪ Capacity information ▪ Data synthesis and depuration ▪	▪ Disassembly of components ▪ Recyclable materials
Cell	▪ Modularity ▪ Inflexibility	▪ Modelling and simulation for the co-design or processes ▪ Re-configurability	▪ Safety boundaries ▪ Fault diagnosis	▪ Buffers ▪ Load stations ▪ Partial robot automation	▪ Inspection flow	▪ Agile manufacturing ▪ Customised products	▪ Yield information	▪ Revenue of components ▪
Shop floor	▪ Use of production resources ▪ Cross-company cooperation	▪ Product traceability ▪ Product tracking ▪ Human-robot interaction	▪ Cybersecurity ▪ Fault diagnosis ▪ Advanced sensing systems	▪ Illumination ▪ Sensors ▪ Databases ▪ Integration with technology	▪ Inspection along the manufacturing process	▪ Lot size ▪ Lead times to produce low-cost high-quality products	▪ Supply chain coordination	▪ Classification of components ▪ Disposal of individual groups ▪
Factory	▪ Minimisation of raw material and energy consumption ▪ Adoption of information and communication technologies ▪ Manufacturing strategies	▪ Flexibility of supply chain ▪ Connectivity ▪ Modelling and simulation ▪ Dynamic plant models	▪ Autonomy and self-organisation of factory ▪ Networked control systems ▪ Emergency routes ▪ Civil protection	▪ Robot logistics ▪ Real-time management ▪ Big Data analytics	▪ Inspection of finished products	▪ Requisitions	▪ Logistics	▪ Carbon footprint analysis

1.3 Research Questions

Considering the challenges that exist at the different levels of manufacturing entities coupled with the S^3 System concept, the main goal of this doctoral research is to present a reference framework able to support the development of the Sensing, Smart and Sustainable manufacturing process (S^3 Process) during manufacturing design. The secondary objective is to lay the foundations of the S^3 Process concept, that is, to identify the actors and understand how they interact and influence the development of novel processes and how to innovate on them. The last objective is to demonstrate how the proposed reference framework could contribute at least to i) design manufacturing processes with S3 solutions based on a product, ii) characterise existing manufacturing processes and improve their S3 attributes. and iii) selection of S3 solutions in manufacturing processes.

The research questions were selected based on the challenges facing manufacturing and the gap in the literature that specifies how to achieve it. The research questions for this work are presented below:

- What are the best practices for the design of manufacturing processes, and what stages of development, tools and activities are required to achieve it?
- For the automation of manufacturing processes, could the S^3 concept be used as an enabler, and what variables should be taken into account, how are the levels and degree of automation defined, what solutions exist and who are the main actors in this development?
- Are there guides for the characterization, design and redesign of current manufacturing processes and how would these guides allow to face current challenges in the industrial sector?

1.4 Solution overview

This research aims to generate a reference framework that can positively influence both the manufacturing and educational sectors promoting the entrepreneurship culture, maker movement[1] and fostering the incubation of companies for economic development. Traditional enterprises occupy a position in the market; however, new manners to compete are global, modular, flexible, customized, among others. Enterprises' ability to respond to consumer demands adapt to changing markets and maintain high-quality processes justify this research. After a comprehensive literature review, it is identified that there are no approaches that fully satisfy all the requirements for enterprises to develop for new digital customers in a changing market. It is necessary to offer a new framework, trends and a toolbox to provide new emergent technologies into the central core of an enterprise, the manufacturing process. The main objective is to fill the gap of design approaches to develop or adapt current operations with the S^3 concept.

To achieve the main objective, it is necessary to consider that the innovations present in manufacturing firms are usually gradual and are gestated once their impact on the organisation's competitive advantage is understood. Competitive advantage theory (Porter & Kramer, 2002) suggests that everyone is better off if decisions are made based on the competitive edge at all levels – national, corporate, local, and individual. Stated, it is nothing more than asking for optimal utilization of resources and the globalization of manufacturing and services across the world.

MSMEs continue to be the workforce of nations, especially in developing countries, which is why the automation ideals of I4.0 seem not to be achievable for all market competitors; however, situations win Winning can be established from the operation of what creates value in organizations. In this way, an opportunity is set for each of the players in the global market

[1] This work has an industrial context, however, its application is not limited to a specific size of organization. The maker movement can be associated with micro companies that seek to develop ideas in a structured way. The contribution of this work aims to serve as a methodology for all those who seek to do so from a manufacturing processes entity. Further information can be consulted at the source: MacMillan, T. (2012). On state street,"maker" movement arrives. *Retrieved November*, *15*, 2014.

that has been driven by globalization. This methodology aims to establish the guideline to be followed by each of the competitors regardless of their resources, thus seeking a distribution of wealth and gradual actions that pursue the organisation's objective.

On the other hand, sustaining the performance of the firm (Porter, 2008) is based on a fundamental assumption that adequate employment opportunities are available to leverage the competitive advantage. In fact, the irreplicable resource of any organization lies in harnessing the talent of the workforce. Similar to the rest of the resources, it can be optimized. However, this resource makes use of other characteristics, such as creativity, strengthening of skills and learning that allows solving complex problems. Sustaining the performance of the firm assumes that workforce will move to where they find their best employment opportunities irrespective of sociocultural differences. That's not necessarily the case in the real world, but it's not altogether untrue either.

Manufacturing firms will redeploy themselves to the best possible opportunities available and relocate resources if necessary. However, there may be adjustment pains at an individual level due to lack of support, capability gaps, and financial situations. Obstacles can slow it down but not reverse the trend that offers a beneficial outcome to everyone involved. Organizations must identify what can differentiate them in their environment and take advantage of what makes them stand out to generate value in their sector.

Competitive advantage is intertwined with the resource and capability theory, which emphasizes the differences between organizations to consolidate and generate competitive advantages in their sector. Derived from this theory, an internal analysis of the organizations is made to identify the most relevant aspects and from the outside to propose growth strategies, taking advantage of the differences with the competitors. An organisation's competitive advantage will allow it to identify the systems that enable it to generate value and propose organizational strategies that use its internal and external resources.

There is a clear difference in resources and capabilities (Foa & Foa, 1980). Combining these generates a competitive advantage in an organization (Carmeli & Tishler, 2004).

The type of resources that exists within any organization is classified into two groups:

- **Tangible resources.** They correspond to physical assets; among them are facilities, acquired technology, number of workers, transportation, patents, licenses, and financial resources.
- **Intangible resources.** They correspond to the organizational resources of the company. Among them, the capabilities, attitude and potential of human capital, the systems developed within the organization with the acquired technology, communication systems and organization with the supply chain, investment in marketing to form the image of the company and the relationships this generates.

On the other hand, the capabilities of an organization correspond to the joint inventiveness of the workforce for the development of tasks. These capacities are internal to the organization and are moulded from three main factors:

- **Capability to manage the workforce.** The talent attraction staff can obtain the necessary resources to fulfil the assigned tasks and develop their competencies efficiently. In addition to this, they provide motivation that allows resources to be retained within the organization. This ability to manage the workforce will enable them to reference their sectors and exploit its tangible resources.
- **Operational capabilities.** The set shapes the business process to carry out commercial, process, inventive, innovative and collaborative work activities. These practices usually make up a compendium of attitudes and how to respond to situations that arise. These guidelines allow the operation of the company in a structured way to achieve the stated objectives.
- **Organizational culture.** It is the set of values, beliefs and forms shared by the members of the organization. Corporate culture reflects the thinking and attitudes of stakeholders. This set of standards guides workforce behaviour and dictates what is expected in the firm's long-term vision.

The capabilities of an organization and how it uses resources is what generates value in an organization. Resources and abilities are unique for any organization (Porter & Kramer, 2002). The relationship between the two allows explaining the sustained competitive advantage and growth of the firms. Thus, a competitive advantage can be developed by exploiting the firm's opportunities in its environment.

Even when companies are not aware of the resources and capabilities, they allow them to remain active in their field. The motivator of this thesis is to provide a framework, recognize the trends and provide a toolbox for organizations to acknowledge the resources and capabilities within a manufacturing process that allows integrating new solutions with an S^3 approach. To bring a traditional into a Knowledge-Driven Manufacturing Process (KDMP).

Therefore, the expected contributions of the doctoral research are described. Firstly, the author presents the Integrated Product, Process and Manufacturing System Development (IPPMD) reference framework, the design methodology used during this dissertation. Afterwards, the development of the 'Sensing, Smart and Sustainable Manufacturing Process (S^3 Process)' procedure. Then, the levels of available solutions in the market are summed up in a taxonomy. Furthermore, the instantiated method for stating the developed reference framework (Cortés, Rodríguez, et al., 2018a; Molina, Ponce, Miranda, & Cortés, 2021). Finally, a discussion is provided. The discussion addresses the importance of the definition of S^3 levels inside a manufacturing firm.

The main contributions are listed below:

- C1: The S^3 Process concept. This concept emerged from the necessity of describing the manufacturing process and providing desirable information that allows designers to characterise, develop, or redesign considering S^3 solutions in manufacturing processes.
- C2: Taxonomy of levels for S^3 Process solutions are described as a reference guide to develop or redesign manufacturing processes.
- C3: Partial instantiation of the IPPMD reference model to provide the S^3 Process Development Reference Framework. It is expected that the framework proposed will fill the current lack of design approaches to create or upgrade existing manufacturing processes into S^3 Processes.
- C4: Case studies where the S^3 Process development reference framework is presented.
- C5: A discussion of the importance to define different levels of S^3 solutions inside a manufacturing firm.

1.5 Thesis organisation

This Thesis is organised into seven chapters. The organisation is represented in Figure 1-7.

Chapter 1 introduces the research domain and states the aim, motivation and scope of the research project.

Chapter 2 shows the IPPMD methodology used throughout this work, which is used to develop products, processes and manufacturing systems. This methodology corresponds to a reference model. Therefore, it emphasises the viewpoints contemplated by its implementation.

Chapter 3 presents a literature review of the Manufacturing Process. The fundamentals, how a manufacturing process is composed and typical manufacturing processes classification.

Chapter 4 presents the 'S^3 Process Development Reference Framework' concept. It contains the definitions for each attribute in a manufacturing process, uses of the S3 Process concept, levels of the attributes, development of the reference framework, toolbox and methodology used in the case studies. This chapter summarizes the contribution of the research work.

Chapter 5 presents case studies using the S^3 Process Development Reference Framework. The first one is referred to develop a new machine, the 3D Food Printer. The second one is attributed to the redesign of the lathe module of the Reconfigurable Micro-Machine CNC Tool. The third one explores an industrial case for the adoption of technology in the leak test, using the exposed methodology and tools. The beneficiary corresponds to a tier-one supplier in the automotive sector.

Chapter 6 discusses the importance of defining different levels of Sensing, Smart and Sustainable attributes in manufacturing processes and the results obtained from this work.

Chapter 7 points out the major conclusions of this research and proposes areas for further analysis. Also, it shows the benefits and limitations identified applying the reference framework proposed.

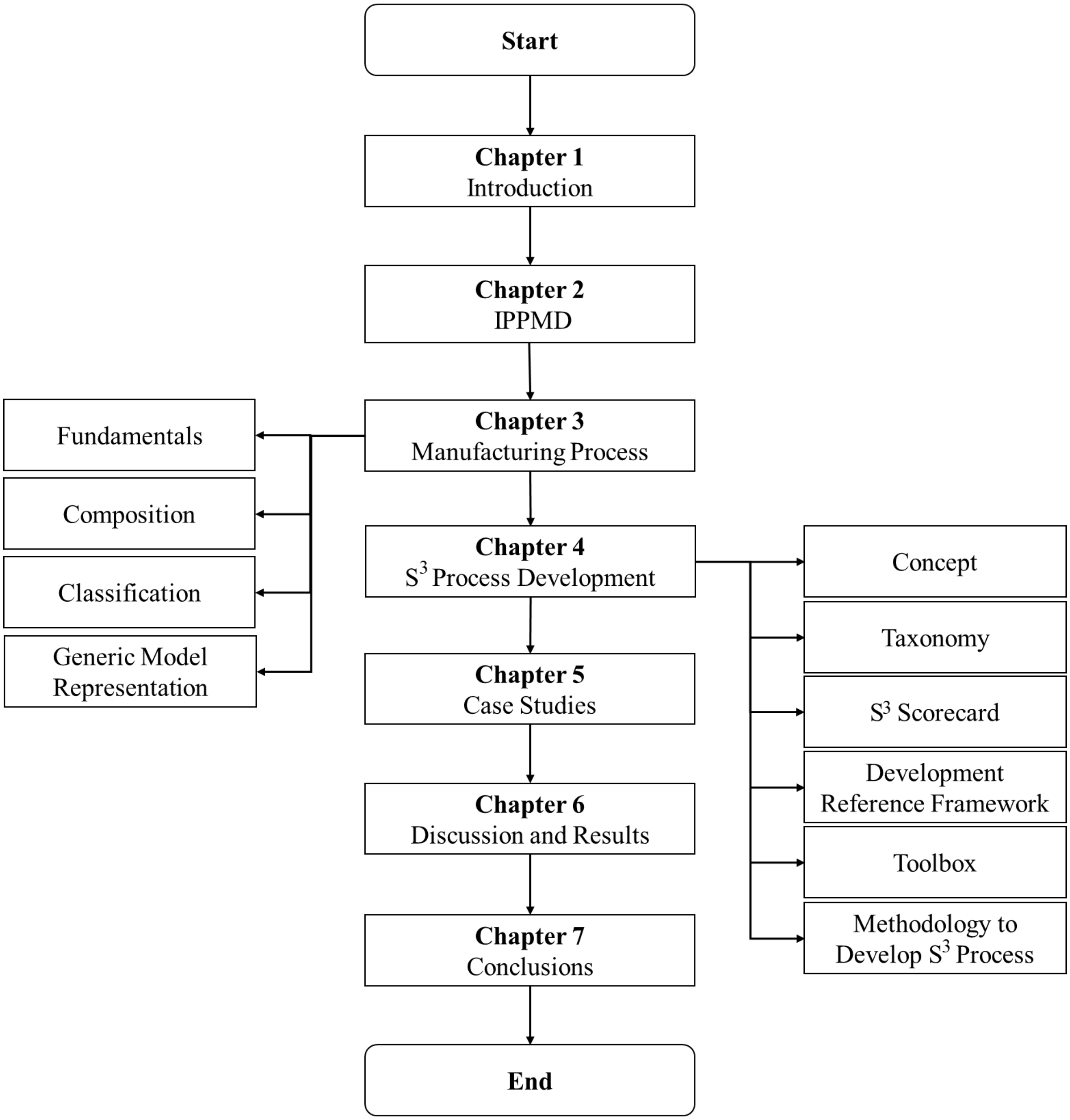


Figure 1-7 Thesis organisation

Chapter 2 Integrated Product, Process and Manufacturing System Development

This chapter delves into the methodology used to develop the S^3 Process Development Reference Framework. The base methodology corresponds to the IPPMD, which has been used for the design and development of various products, the manufacturing process that allows them to be developed, start-up of manufacturing systems, as well as renewal of educational courses, bootcamps and complementing the documentation for the bases of business model creation. This methodology was previously tested in sixteen-week semesters, three intensive online courses, seven-week summer courses, and fourteen-seven-day camps. Each case has provided the participants with a structure to develop the entire production system for emergent markets. The model is simple to understand in the different stages of operation but robust since it combines points of view, tools and engineering activities to develop multidisciplinary projects. It makes use of concurrent engineering to converge tools and multidisciplinary design points of view. It comprises four design stages for creating three manufacturing entities (see section 2.2 in this chapter). This model was built from design practices, analysis of engineering activities, good customs for project development, documentation necessary to share information in the different areas of the manufacturing firm and, in general, considering the industrial context of any organization. Therefore, its use can be used in any context, for the new design of entities, redesign of existing entities or functional decomposition and analysis of the various stages that make up an entity. The IPPMD aims to provide a structure to anyone who wishes to design and establish entity requirements from any scope. For this reason, the methodology has been used as the basis for the development of this work. The objectives to be achieved using this methodology, the IPPMD model and the manufacturing process entity are described underneath.

2.1 Knowledge-driven Manufacturing

Due to the increasing acceptance of technology in the productive sectors and the variety of existing solutions, organizations of all sizes seek the acquisition of devices that allow them to control their production chain. In manufacturing trends, multiple technologies complement each other, such as Cloud Computing (CC), mobile technologies, the internet of things; solutions that aim to diminish distance barriers and allow information sharing. This phenomenon is not typical of the industrial sector but rather phenomena derived from social megatrends that seek to bring society closer together through technology. This has allowed an exchange of accessible communication in all directions and has generated an opportunity for manufacturing firms since the dissemination of the goods they offer and the feedback on them comes in a short period from their commercialization. By virtue of this, organizations are now more aware of what it takes to keep track, communicate effectively, get short-term information, and the benefits of making decisions based on real-time data (J. M. Müller & Voigt, 2018).

This fact derives mainly from the influence of the pillars of I 4.0 (Dalenogare et al., 2018) and offering quality products and services to the communities. The inclusion of technologies has allowed establishing a direct conversation with the rest of the stakeholders, but especially with consumers and even considering their participation for organisations' continuous improvement, breaking the traditional paradigm and turning it into a prosumer (Kotler, Kartajaya, & Setiawan, 2016). The figure of a prosumer was limited in traditional manufacturing due to the lack of communication infrastructure and the selection of a specific niche to improve products or services by the organization.

The foundation of traditional manufacturing is the speculation in market trends, making production lines rigid and thereby reducing costs to offer a good or service for a price that the market would accept. Nonetheless, including the consumer as part of the design and customization of the product, taking advantage of communication channels, allows real-time feedback on the needs they have, the functions they seek, and how their beliefs match those of the organization. Offering a brand concept instead of just products. Therefore, manufacturing companies must perceive consumers as a fundamental piece that allows the diversification of current products or personalization of existing lines.

Moreover, manufacturing companies constitute a fundamental role, as they generate jobs, growth in the region and professional opportunities for multiple areas. Nevertheless, MSMEs still represent the working force capacity of developing countries. The main advantages of these manufacturing firms are the flexibility of their production lines (Cronin et al., 2019) and the fast response to introduce novel products.

Although manufacturing firms offer opportunities in their region, they also seek to prevail over time and expand their market presence (Koyuncu, Firfiray, Claes, & Hamori, 2010). Therefore, they are looking for inventive personnel who know about techniques, methodologies and tools, capable of adapting new technologies to traditional systems. It is crucial to highlight that the strength of an organization lies in the added value to its clients, but above all in how it does things differently from the rest of its competitors, the intangible resources of the organization, how it carries out its manufacturing processes.

The first contact of undergraduates with these new trends occurs within the universities. However, the requirements come from the industrial sector and government planning for the progressive development of nations. This joint development is known as the triple helix effort (Lee et al., 2020), supporting processes or techniques research and development. The actors include the Academy, Industry and Government. This interaction promotes the development of policies, seeks the solution to applied problems for the industry and seeks an exchange both of knowledge and for the benefit of students who work on the issues in the industrial sector.

According to a Price Waterhouse Cooper's article called "The World in 2050" (Price Waterhouse Coopers, 2015), most of the economic power will be transferred to the so-called Emerging Nations (E7) in the middle of the 21st century. This will result in profound transformations in their commerce, education and industry. An unprecedented increase in the consumption of goods and services will require innovative ways of producing them (Hehenberger, 2009). Innovation among the enterprises needs to follow and respond faster to growing demands of the novel, high quality and more personalized products and remain competitive in the globalized markets. Therefore, more than ever, enterprises must be aware of the challenging environment to assess and recognise their capabilities to face the competence and forecast upcoming events.

According to Koren et al. (1999), there are five significant challenges to traditional manufacturing systems: i) increased frequency of new product introductions, ii) part upgrades for existing products, iii) product demand fluctuations, iv) changes in government regulations around the world and v) changes in process technology. Due to companies' international presence, it is common to find alliances and collaboration that allow companies to stand out from their competitors. Then, for manufacturing firms to cope with their dynamic production and aim for covering the market demands (Bainbridge & Roco, 2006), they have been testing for different technological alternatives to improve multiple areas of the business model (Weichhart, Molina, Chen, Whitman, & Vernadat, 2016). This takes place at different levels, often involving the industry-academia duo. This synergy between entities has brought shared benefits. To the academic side, the understanding of the theory from business and how to blend a multidisciplinary view to a systematic approach, and for the industry side, the adoption of novel research technologies to the extent that allows the optimization of their productivity and expand the understanding of their environment.

Emergent technologies have aided in the manner manufacturing firms conceive, produce and bring to the physical world innovative solutions for the welfare of society (Shamsuzzoha, Helo, & Sandhu, 2016; Tewari, 2005). With the increased capabilities of computer hardware, the cost of some technologies has reached such an affordable point that they are becoming ubiquitous. This has led to innovative solutions to embrace manufacturing challenges that require adaptable and responsive production lines. The adoption of multiple sensors, smart capacities, CC, industrial internet of things (IIoT), Big Data (BD), cyber-physical systems (CPS), virtual (VR), and augmented reality (AR), among other technologies, have been used to collect, process and share information horizontally and vertically among enterprises to accelerate the decision-making and monitor real-time operations (Suginouchi, Kokuryo, & Kaihara, 2017). Novel practices are intended to exchange information, automation and decision-making in real-time as their primary objective.

Among the industrial sector with the most benefits from technology adoption (Kashyap, 2019; J. M. Müller & Voigt, 2018), manufacturing firms stand out due to the complexity of the infrastructure and the multiple operations that are carried out. It is important to note that even considering previous enablers, the firm's value proposition enhances its position in the sector (Molina et al., 2021; Porter & Heppelmann, 2014). For instance, manufacturing firms play a fundamental role in developing countries productivity as they offer workplaces and incomes on average 25% of their GDP (The World Bank & OECD, 2018). MSMEs present inherent advantages in the flexibility of their production lines when compared against more prominent competitors. Thus, they can respond faster to emergent demands (Cronin et al., 2019). Their numbers make up 97% of the manufacturing firms in some developing countries (INEGI, 2018). All in all, there are multiple areas where MSMEs propose innovative solutions coupled with emerging technologies but end up ceasing activities in their first years of existence mostly due to the lack of structured processes to guide good manufacturing practices and improvement on the value proposition. The collaborative work from academia with other stakeholders and detailed research about market tendencies allowed to understand the importance that MSME will have in the medium-term future. There is a particular interest among educational institutions, the entrepreneur community and the maker movement in adopting new manufacturing systems and design methodologies to cope with the upcoming challenges.

In recent years, there have been significant advances in technological adoption and industrial environmental knowledge (Dehning, Lubinetzki, Thiede, & Herrmann, 2016)(Liu, Teng, & Han, 2020). Targeting these two competencies, intend to exchange information, automation and decision-making in real-time as their primary objective. These technologies involve monitoring hierarchy, material and information flow inside production lines to sense, collect, process and share data at vertical or horizontal departments of the business model (Suginouchi et al., 2017). These practices promote technological solutions and aim to migrate traditional into KDMP, where processes are modular, production lines are flexible, operations are monitored and updated in real-time due to data collection and processing. The last competency is related to sustainability. The inclusion of sustainability in modern manufacturing systems provides manufacturing firms with a long-term vision while generating incomes and positive impacts in other areas. Sustainability is understood in three levels (Lowe, 2005; Tewari, 2005): i) economical, ii) social, and iii) environmental. Therefore, a manufacturing firm must develop goods not only receiving economic gains but also offering society a positive impact, working conditions and retrieving the finite resources to the environment. Modern manufacturing systems ought to include S^3 solutions. Thus, including these characteristics in a manufacturing firm allows adapting technology for monitoring and decision-making in real-time while pursuing long-term sustainable objectives.

Considering the competencies of an MSME to continue its operations, the adoption of technology to monitor the production chain and the attributes necessary to bring traditional into KDMP, the taxonomy of S^3 levels in manufacturing processes is proposed delved in Chapter 4. However, to get from the current point to the adoption of technology and allocate resources efficiently, it is necessary to provide a structure that acts as a guide in developing knowledge-driven manufacturing processes or improving those currently available from manufacturing firms. In this sense, the IPPMD reference framework has been used to carry out this process. The following section describes its parts and usage during the development process.

2.2 Integrated Product, Process and Manufacturing System Development

The use of Reference Framework (RF) has spread in the industrial field to provide structure, consistency, reproducibility, collaboration and transmit expertise on a topic. It emphasizes the best practices to carry out tasks and implement concepts. In this way, an RF reflects the knowledge acquired and the steps to be followed in a specific area. An RF is comprised of both i) architecture and ii) concepts and their interrelation (Zhang, Ming, Liu, Qu, & Yin, 2019). Therefore, an RF is useful for those with knowledge of the topic, especially those who dabble in the subject. Besides, an RF provides viewpoints gained from practice and implementation, decreasing errors to newcomers and saving time while deploying projects (Wilkes, 2012). Its importance lies in the transmission of knowledge to new generations.

Enterprise integration in a manufacturing firm contemplates the phased development of products, processes, manufacturing systems and business models. CIMOSA is an RF that integrates these entities in a modular approach (Vlietstra, 1996). New trends in manufacturing have proven worth in CIMOSA as a complete approach to analyse and define the parts of an enterprise as a set of subsequent modules. During the design process and deployment, it provides benefits about i) simplification of the business processes throughout process flow of control and information, ii) evaluation of alternatives through simulation of operations, iii) business management of organization assets responsibilities and authorities and, iv) the reduction of lead times through the sharing and reusing of information, allocating the modifications and extensions of the business model.

On the other hand, PERA is another RF that aims at decision-making and control hierarchy (Williams, 1994). It is also a design enterprise architecture that seeks to provide structure in: i) the physical process, ii) intelligent devices, iii) control systems, iv) manufacturing operations systems, and v) business logistics systems. Nonetheless, both approaches aim to cover the integration and interrelation of the entities. Therefore, the are ongoing efforts to protect the rest of the entities that comprise a manufacturing firm and treat them as individuals with their own architecture and concepts. The specialization of these RF by entity helps the documentation and development of entities in the industrial sector.

In the search for architectures that provide information about the entities of a manufacturing firm, the following design methodologies have been found consistently since 2016 (See Figure 2-1): Instructional System Design (Lewandowski, 2019), Design Thinking (Nyemba et al., 2020), Agile Design (Riesener, Rebentisch, Doelle, Kuhn, & Brockmann, 2019), System Thinking (Hassmiller Lich, Urban, Frerichs, & Dave, 2017), X Problem (Bertsekas & Gafni, 1982), Biomimicry (Benyus, 1997), Response Surface Methodology (Khuri & Mukhopadhyay, 2010), among others. However, most of them are oriented to design the first entity in a manufacturing firm, product, and fail while designing and developing manufacturing processes or entire manufacturing systems.

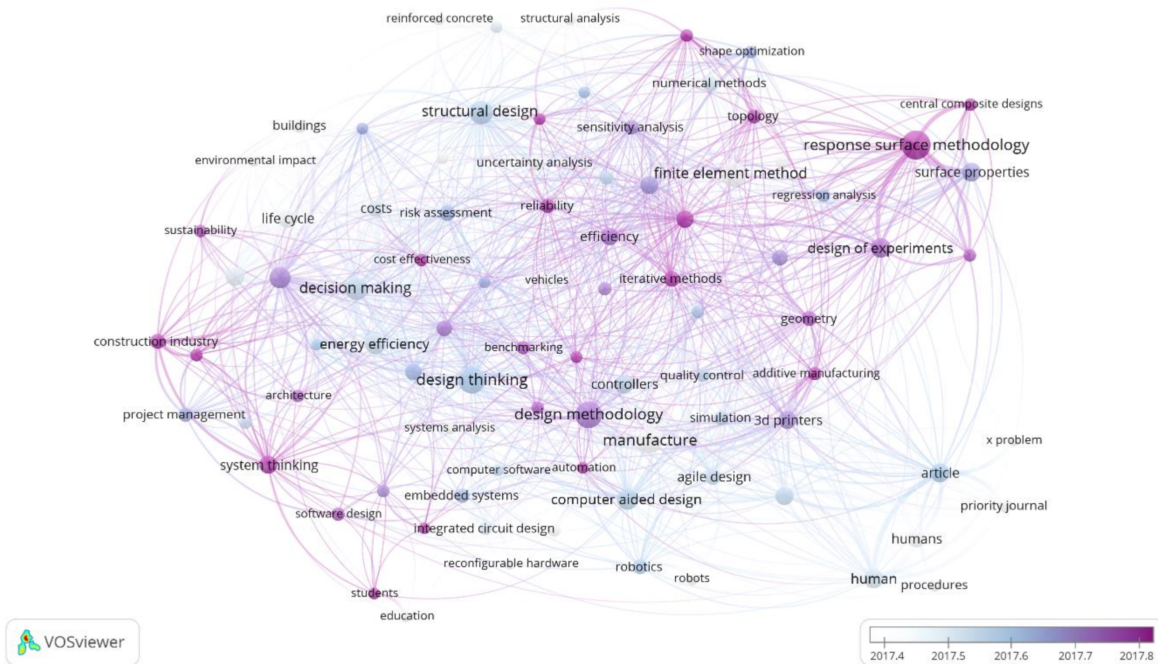


Figure 2-1 Design methodologies

Considering those mentioned above, within the RF that comprised the rest of the design entities in a manufacturing firm, there is a model that is based on the principles established in CIMOSA and PERA, but at the same time, integrates the design stages present in the trends of the methodologies analysed. Thus, its objective is to provide structure, consistency, reproducibility, sharing the expertise and guiding designers throughout the entities of a manufacturing firm.

The Integrated Product, Process and Manufacturing System Development (IPPMD) is an RF that arose to aid in the innovation design process among the manufacturing sector. The IPPMD is understood as architecture and interaction of concepts that depend on engineering activities to document the entities development. It gathers existing knowledge to provide structure, systematize the development, allocate problems and provide feedback during the deployment. It uses techniques, procedures, experiences, and norms that apply to the context of the manufacturing sector of the project, where it aims to be instantiated. It is possible the systematic evaluation of tollgates that justify the progress or rejection of specific steps during its implementation.

Its effectiveness has been tested under multiple scenarios, disciplines and time-lapses. Some of the applications include: i) redesign of integrated manufacturing system course of sixteen weeks, offered at Tecnologico de Monterrey for System and Industrial Engineering (Chavarría-Barrientos, Miranda, Cortés, & Molina, 2018), ii) summer research stays of seven weeks (Cortés, Ramírez, & Molina, 2018) from Academia Mexicana de Ciencias and Programa Delfin to strengthen research and postgraduate studies, as well as the exchange of scientific and technological production in the region of the pacific in Mexico, iii) development of technology for the Reconfigurable Micro-machine Tool 1G (Ramírez-Cadena, Miranda, Tello-Albarrán, Dávila-Ramírez, & Molina, 2012), iv) as part of a binational project between Colombia and Mexico to conceptualize a 3D Food Printer system (Cortés, Rodríguez, et al., 2018b) v) to teach rapid product development for makers and entrepreneurs in a free massive open online course (Molina, Romero, & Ponce, 2016), vi) in collaborative networks (Cortés, Chavarría-Barrientos, et al., 2018), vii) transferring the concept to enterprises (Chavarría-Barrientos et al., 2017), among others. This robust framework can exceed the traditional manufacturing systems vision and be extrapolated on any object conceived as a system such as business models, communities and even cities. However, the scope of this work is focused on the development of a manufacturing process entity.

The construction of the IPPMD is detailed in chapter 2 of Molina et al. (2021). It describes the structure of the RF, the activities that must be carried out to advance between design stages, the manufacturing entities that can be developed with it and the industrial applications. In addition, later chapters detail the development of Products, Manufacturing Processes and Manufacturing Systems using the IPPMD. To create these manufacturing entities, it is necessary to understand the design stages and instantiate the model in the industrial context. The applications of IPPMD RF are diverse due to the simplicity in which it presents the stages. However, its development involves integrating multidisciplinary information and effort by a development team specialized in the sector of the manufacturing entity.

The IPPMD RF gathers entities, engineering activities, stages and viewpoints to create an entire Integrated Manufacturing System (IMS), providing structure for those that follow the entire cycle. The basic structure of the reference model is as follows: i) Entities, which compose the system of a manufacturing firm and, ii) Stages, which are the design steps that must be followed during the creation process (Chung, Choi, Ramani, & Patwardhan, 2005). IMS consists of three essential entities that must be developed inside a manufacturing firm. These are i) Products, which are the main motive of a firm, ii) Manufacturing Processes, to elaborate the products and which define the space, time and resources needed to be productive and the iii) Manufacturing System, which establishes the parameters to be carried out during the entire cycle and contemplates both, internal and external resources of the value chain. The stages guide developers along the creation process (See Figure 2-2). There are four essential steps among this process: i) Ideation of the current entity, which analyses the introductory scene and determines what must be done ii) Basic Development which arises the minimal requirements to the following stages, iii) Advanced Development which faces a model of the current entity into a scenario that could be presented and, iv) Launching which analyses the behaviour of the entity in the physical world. At the end of each stage, a tollgate is achieved to gather the creation cycle evidence and allow feedback to the development team.

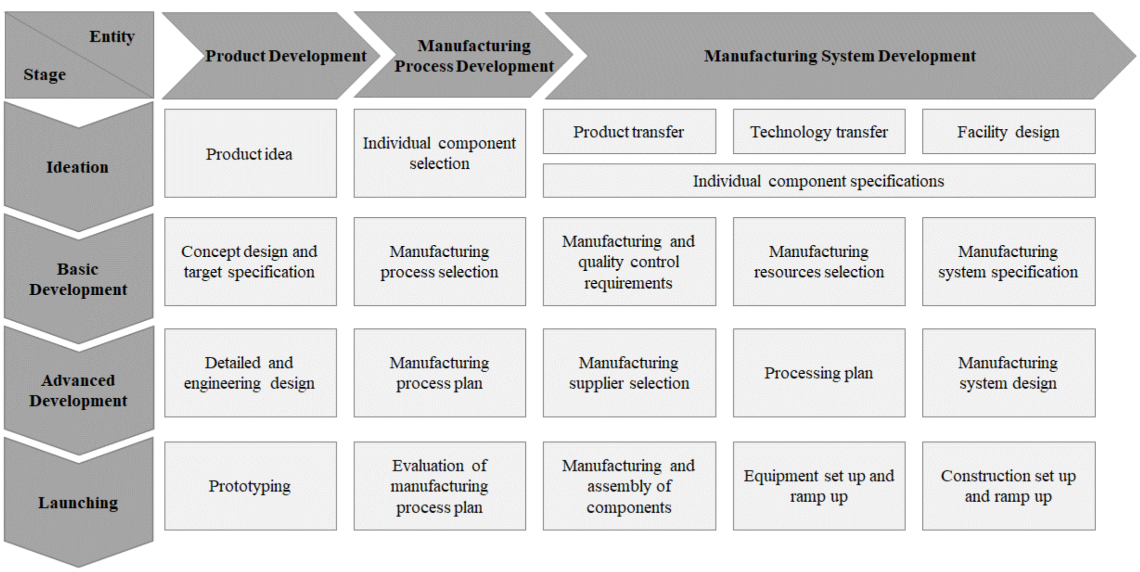


Figure 2-2 Integrated Product, Process and Manufacturing System Development (IPPMD) Reference Framework

Every intersection of Entities and Stages is described in terms of their function, information, resources, and organization (Ragatz, Handfield, & Petersen, 2002)(Ratchev & Hirani, 2001). To enrich the development process, at least three engineering activities are required: i) analysis, ii) synthesis and iii) evaluation. Therefore, even though the IPPMD RF is a simple figure representing entities along the creation process, some ongoing activities and viewpoints must be covered throughout an entity's development. Arguably, the IPPMD RF is an unambiguous and precise representation of Figure 2-3 which implies the Development Partial Model (DPM).

The latter seeks to cover specific activities in the different viewpoints from which the development of the entity can be analyzed. Each of the models has its application from the design point of view. However, the DPMs focus more on concurrent engineering, while the RF ones emphasise practical application from the systems point of view for developing specialized projects. In contrast, the former model seeks simplicity in various contexts with manufacturing rules specific to each sector.

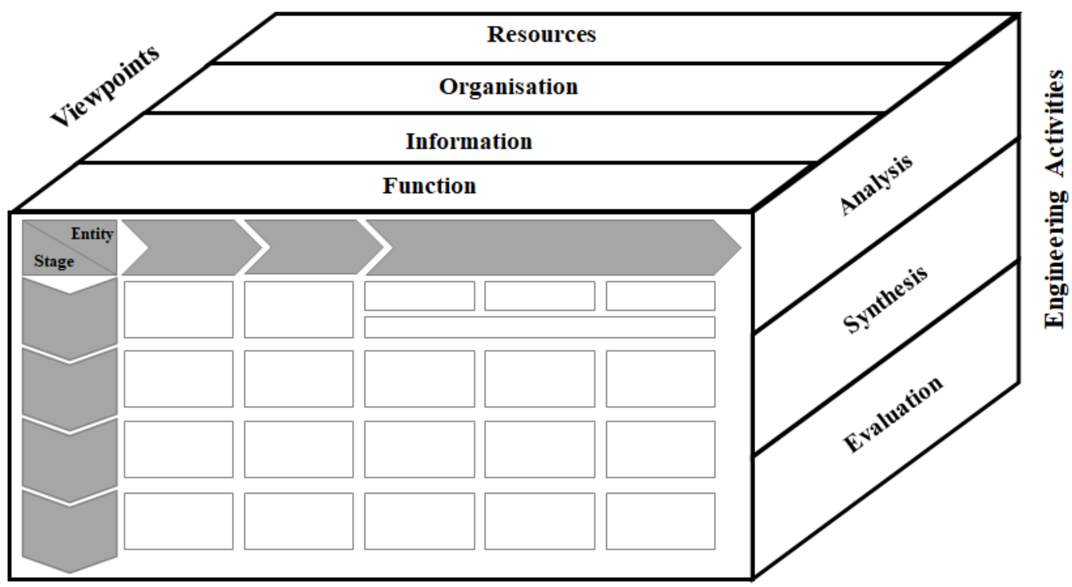


Figure 2-3 IPPMD development partial model

Another manner of understanding these interactions is that the IPPMD consists of viewpoints that conform to the IMS and, to develop the entities, it is necessary to achieve engineering activities. Thus, to create the three entities, engineering activities must be carried out in a systemic order to assure robustness in defining goals. Figure 2-2 depicts the reference framework where indeed stages are supported by engineering activities that consider the multiple relevant viewpoints for a manufacturing system.

The IPPMD includes three entities. Its application has been used for the development of products and to build its manufacturing process together with the manufacturing system that allows its growth. However, its application can be extended to different scenarios, considering the creation stages, viewpoints and engineering activities. Nonetheless, as seen in the manufacturing design overview (Table 1-1), the product entity has deepened in the past, but there is still a gap to fill in the following stages.

For the development of projects in the industrial environment using the IPPMD, three stages need to be defined in a systemic way presented in Figure 2-5 1) Business requirements that collect information about the project and the scope it will have, 2) Process trajectory using the IPPMD and considering the capacities and capabilities of the organization and 3) Information flow to verify the progress of the development of the entities. Thus, from the second stage, the tollgates are obtained that are milestones at the end of each of the numbered stages together with the documentation that evaluates the development.

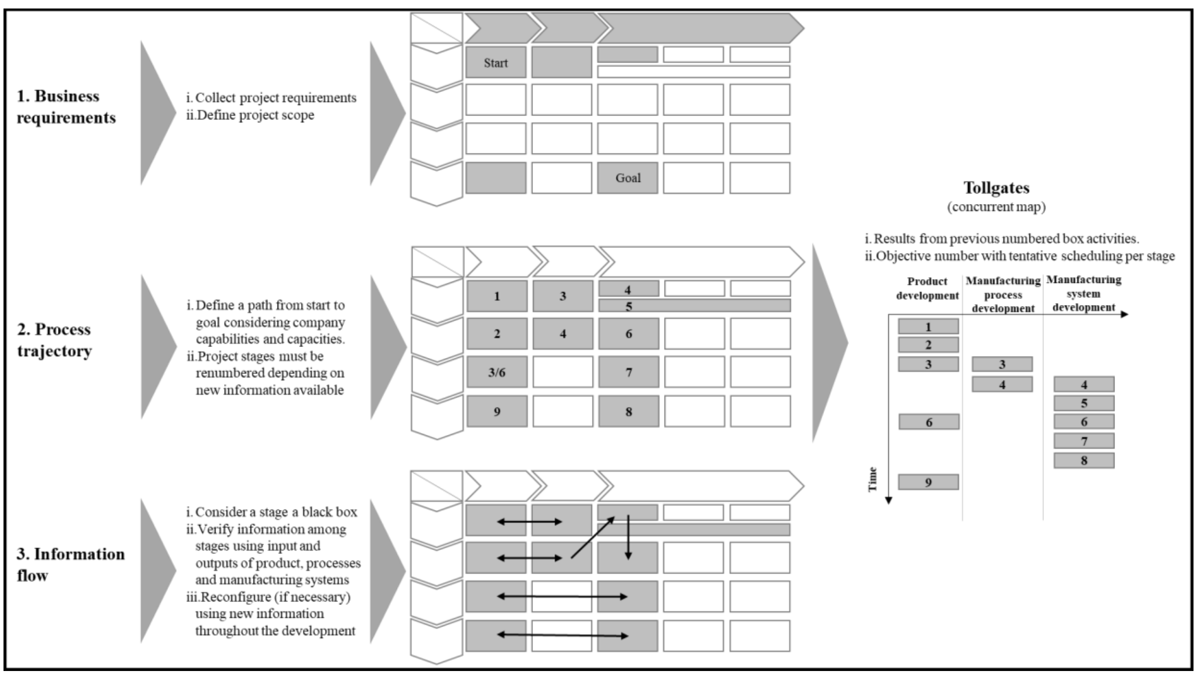


Figure 2-4 Project definition using the IPPMD

Due to the natural development of this research line, this thesis dissertation focuses on the entity of the manufacturing process as shown in Figure 2-5, which will be deepened in this document. The reference model has been used to lay the foundations of the three entities and has been contrasted with business models to identify the vertices of this application. It has proven to be a robust and versatile model in different manufacturing areas.

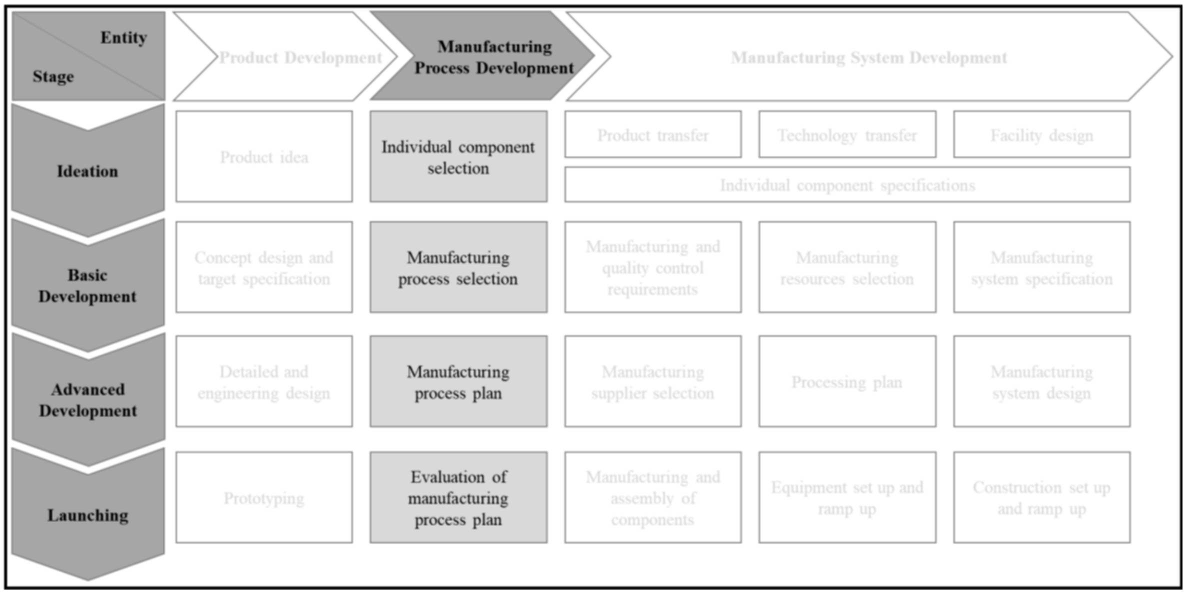


Figure 2-5 IPPMD for manufacturing process development.

2.3 Process Entity

For the design of an IMS, the manufacturing process is the second entity. This definition is the one that will be used for the work; it can be corroborated in Figure 2-2. This is developed after the product since it allows to identify each of its needs and requirements. In addition, the process analyzes the functions offered by the product entity. Due to this, it is required to know its components. In this, actions are carried out that bring together various areas of the manufacturing firm and consider an effort to create value.

In summary, the manufacturing process is where the product is abstracted from the concept and materialized to generate value, seeking to take advantage of the firm's resources to do so with the least effort and the highest quality. These points are noted in the literature and provide a purpose to begin developing the process. In practice, this process comprises at least two considerations i) the stages necessary to develop the product and ii) the resources required to achieve it. The good practices of the design of a manufacturing system also consider the organisation and the information to complete a practical development. In this way, the four viewpoints of the partial model for the process in a manufacturing firm are covered (See Figure 2-3). In addition to fulfilling the engineering activities for the documentation and systematic development of each of the stages.

This entity is the backbone of a manufacturing firm since it compares the market information by-product and allows defining the steps to do so, the required spaces, the quality parameters, the times, the ways to execute, the machinery and necessary tools. The process also provides context for the product to be developed, adheres to regulations, considers physical or mechanical essential points to carry out specific actions, consider the different methods of carrying out an activity in terms of their function execution time and promotes the development or adoption of technology as a basis for the design of the manufacturing system. It is the entity responsible for generating value within an organization from the practical point of view of a good or service offered.

It might also be noted, in this subsection (2.3), the word Process has been used to define the second entity that corresponds to the IPPMD, since in the conception of the RF, the distinction between a manufacturing process and a business process is not made. In fact, both concepts are closely linked, and both can be characterized following very similar stages. However, as one delves into either of the two topics, characteristics that differentiate them are observed, techniques and concepts usually interchanged in both contexts. However, they do not represent the same thing. For these reasons, it was decided to treat the entity as two different concepts. Both are explained below. However, only the former will be a source of interest in this document, and the latter will be the subject of interest for further research.

2.3.1 Manufacturing Process

Manufacturing process is referred to the steps required to transform raw material into final products (R H Todd, Allen, & Alting, 1994). It uses different methods to select physical or chemical transformations to choose the economically best manufacturing sequence. The manufacturing process begins with the physical definition of the product and the functional solutions offered in it. Therefore, an analysis of geometries, materials, surface finishes and tolerances are required.

To carry out an analysis of these attributes and complement the requirements of most industries today, a model of the manufacturing process has been defined that will be exposed in Chapter 3. The features disclosed in the model respond directly to the overviews for the manufacturing systems, while those areas of interest for the firms are exposed. The model follows the structure of the IPPMD RF for the second entity, so engineering activities are described for documentation and development. According to the decomposition of a manufacturing process and the study of the literature, it was found that the general physical scheme of a manufacturing process requires at least the following information as inputs and outputs i) material, ii) information, iii) services and iv) energy. These inputs and outputs are transformed during the manufacturing process that is carried out, so the resources must be measurable. These resources are defined from the first entity. However, the selection of the manufacturing processes and the goods offered must be consistent with the organization's objectives in the short, medium, and long term.

2.3.2 Business Process

Because manufacturing firms operate under organizational processes, these processes have behaviour that the second entity of the IPPMD could describe. However, the former refers to the stages of creation and interrelationships throughout the supply chain (Harrington, 1994). This organizational process is distinguished from the manufacturing process because it represents the operations that must be carried out administratively and during the operation of the manufacturing firm. Therefore, they are known as business processes. Similarly, the term business process can be confused with a business model; however, the latter contemplates creating a unit dedicated to obtaining a benefit from exchanging a good or service. Furthermore, the business model is generally the result of analyzing the IMS and the value chain. Business processes are focused on the optimization of resources for commercialization and internal and external business relationships.

The business process begins with defining an objective, a series of activities are drawn together to define their individual units and finally connects the corresponding areas for their execution. Throughout this process, it is necessary to identify the key points that generate value since the business process connects them through the supply chain and activities of the organization itself. That is, it connects external and internal stakeholders. In essence, it executes the same actions as a manufacturing process and starts from the exact origin, the definition of the product. Throughout this process, the generation of value can be traced as well as the materials, information, services and intangible resources. This allows optimizing resources and connecting various departments or areas of the business to produce products and meet organizational objectives.

Within the business process, it is necessary to identify the areas that make up the manufacturing firm, the external actors, the decision-makers that contribute to the creation of processes and finally, the core processes. Figure 2-6 offers a schematic representation of the business process and the areas that comprise it (Browne & Zhang, 1999; Jagdev & Browne, 1998). In this manner, there is observed that the processes are far from each other.

The manufacturing process focuses on the core process of Make, while the business process observes the existing interactions between departments and, from this relationship, seeks the efficient use of resources.

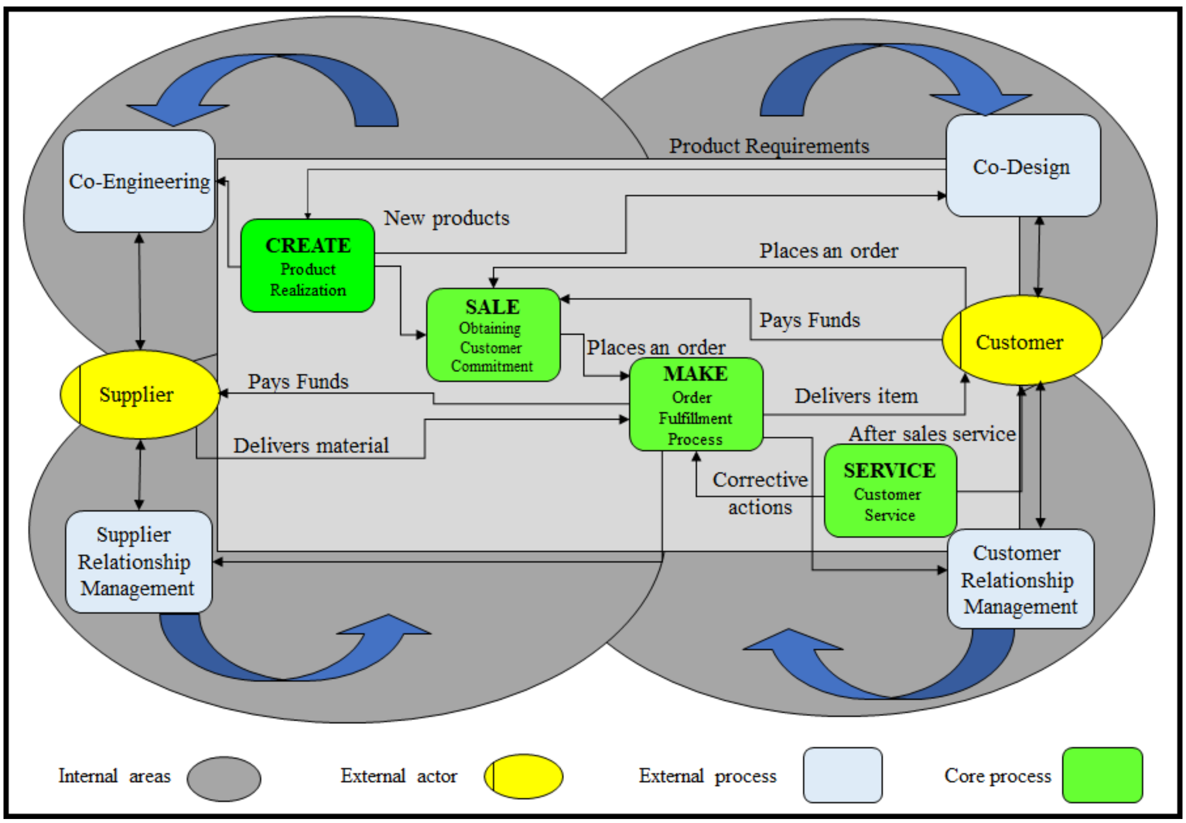
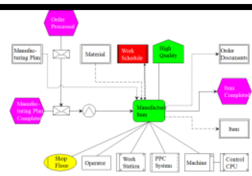
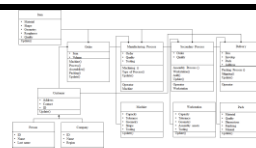
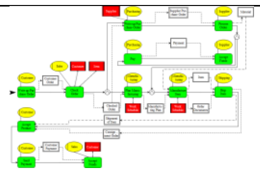
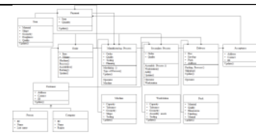
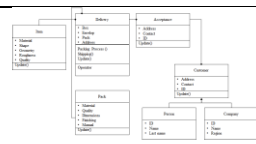
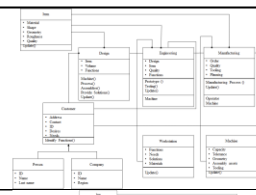
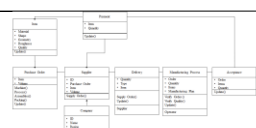
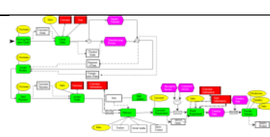


Figure 2-6 Business process entity. Retrieved from (Molina, Sánchez, & Kusiak, 1999)

The business core processes comprise the essential activities for the operation of the business unit to generate value within the organization. However, there are particular situations where the S^3 concept could be implemented. Some of these areas have been identified and are presented in Table 2-1.

Table 2-1 Business process opportunity areas. Retrieved from (Molina et al., 2021)

	Core Process	ARIS Model	UML Model	What to Sense?	When to be Smart?	How to be Sustainable?
Vertical Integration	Product Realization			• Raw material • Finished Products • Anomalies	• Processing orders • Detecting failures • Machines	• Renewable, recyclable and reusable materials • Infrastructure • Machines • Stations
	Order Fulfilment			• Orders • Material • Money • Items	• Processing documents • Supplier • Sales • Schedule	• Machines • Order requirements • No processing wastes • Reusable materials • Recyclable materials
	Obtaining Customer Commitmen t			• Commitmen t • Items • Followers • Trackers	• Contact with customer • Quality of items • Deliveries	• Packing materials • Processing orders
	Customer Service			• Time of service • Common services • Perception of the customer	• Processing requiremen t • Offering solutions • Quality of service	• Renewable, recyclable and reusable materials • Processing orders
Horizontal Integration	Co-Design			• Materials • Customer • Quality variables • Items	• Modelling • Simulation • Validating concept	• Manufacturin g techniques • Materials • Documentatio n
	Co-Engineering			• Resources • Quality variables • Materials	• Modelling • Validating concept • Scheduling	• Materials • Documents • Testing • Validating concept
	Supplier Relationshi p Manager			• Money • Material • Orders	• Processing orders • Receiving material • Testing • Payment	• Documents • Selecting suppliers • Solutions • Manufacturin g process
	Customer Relationshi p Manager			• Commitmen t • Recurrent customers • Sent items • Orders	• Processing requiremen t • Logistics • Contact with customer • Tracking • Processing payment	• Processing orders • Packing materials • Renewable, recyclable and reusable materials • Documentatio n

The similarity between manufacturing and business processes has been presented. However, it was decided to separate both concepts to study each in detail and propose an RF that allows their development in various contexts. As mentioned above, the manufacturing process will be of concern for this thesis, while the business process will be covered in future research. The areas of interest regarding Sensing, Smart and Sustainable concepts are exposed (See Section 4).

Chapter 3 Manufacturing Process

In recent years, manufacturing processes have increased to incorporate technological solutions, ceramic or plastic materials with resistance to metals, miniaturization of existing products, and the addition of processors that allow interaction through communication modules. Throughout industrial history, different manufacturing processes have been observed that guarantee the transformation of the raw material into components that offer value and finally into products that meet needs within society. A manufacturing firm has two types of processes: i) the business process[2] and ii) the manufacturing process. The latter is described along with this chapter and its fundamental components. Over the years, process engineering was in charge of establishing the most relevant parameters for a manufacturing process and together with the interests of the firm. It is possible to prioritize certain variables that encompass the production and effectiveness of the process. As mentioned in Chapter 2, entities developed in the manufacturing field include four viewpoints under good design practices and design efficiency. The views are: i) resources, ii) organisation, iii) information and iv) function. These views help characterize a manufacturing process by focusing on what it is composed of, that is, minimally, the manufacturing processes can be monitored through their variables of i) control, ii) productivity, iii) energy and iv) services, in both inputs and outputs of the process, respectively. From the systemic viewpoint, any manufacturing process can be isolated, and this information would help understand the input and output assumptions of the process. Its reduction would resemble the general black-box model; in this way, there is a model capable of representing any manufacturing process but needs to be contextualized for its study. The control variables respond to the minimum requirements for the actions and processes to be carried out; they have defined a setpoint and manipulable variables to keep the process in control. In it are variables of temperature, friction, movement, among others. Those of productivity respond to a certain number of pieces in a specific time.

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[2] S^3 Business Process would be the central topic of future research and works. For further explanation See Chapter 2, section 2.3.2.

On the other hand, information responds to input and output parameters required to carry out specific actions. The minimum information to carry out components included dimensions, tolerances, shapes, and whether it came from a previous process. Finally, outputs are usually measured as the amount of energy used per hour, equal to the function performed and impacts the manufacturing system productivity. Thus, these variables will be used in this chapter to explain the types of manufacturing processes, background and the generic model used to develop entities using the reference model. Later, Chapter 4 describes the S^3 Process concept to proceed with developing the RF.

3.1 Fundamentals of manufacturing processes

A manufacturing process, in general, is the act of transforming some of the characteristics of the raw material to add value and form part of a finished product. Describing the individual components of a manufacturing process implies knowledge of the phenomena that define it, units, light, sound, dynamics, statics, materials, thermodynamics, fluids, and chemistry (Singh, 2008). Each of the mentioned topics has its research area dedicated to particular processes that can be described using only characteristics of its speciality. However, in practice, the combination of these coincide, and by their nature, manufacturing processes become complex phenomena that involve a multidisciplinary description.

In addition, the study of manufacturing processes is not limited to a particular area. However, today, its analysis represents the intervention of disciplines in materials, product design, production systems, automated systems, control, administration manufacturing, workforce effectiveness, and quality. A query in the IHS Goldfire search engine shows the subject's relevance worldwide. Several patents are associated with the issue exceeding 11 million applications, 217,239 articles, 71,803 standards and manuals of good practices 52,310 engineering books from 2016 to 2021.

Among the most requested topics in the case of manufacturing processes are the definitions of emerging concepts, properties of materials or that are caused by acts of transformation, concepts from different disciplines, advantages and disadvantages of techniques, applications, materials, locations, conditions, but the topic that generates the most significant interest is that of methodologies to carry out their implementation. Only this field has a match of 190,784 cases of the total articles. The variables usually consulted (See Figure 3-1) are frequently related to time, quality, productivity, process duration and, in general, environment variables.

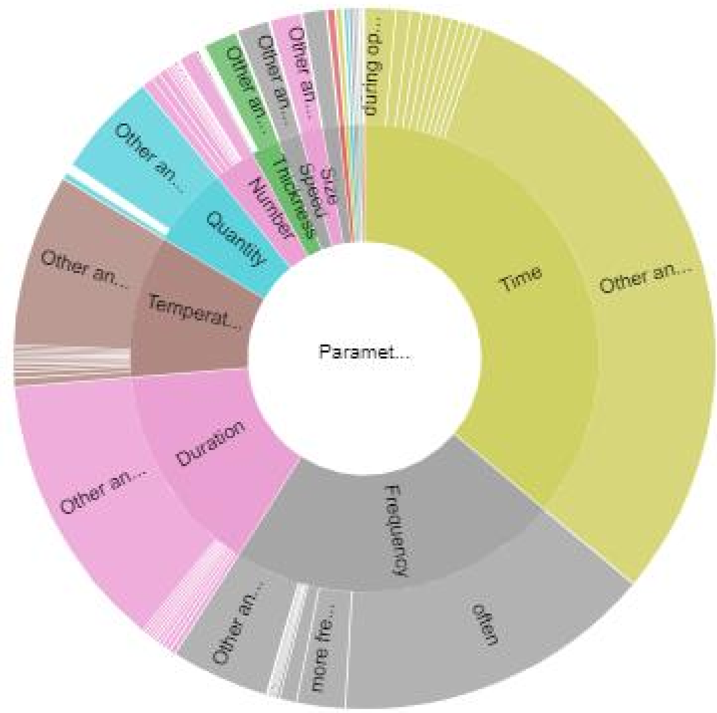

Figure 3-1 Manufacturing processes' relevant parameters. IHS Goldfire.

This bibliographic search reaffirms the relevance of the manufacturing processes, but above all, variables of interest for applications in various fields and the missing methodology to characterize manufacturing processes in different areas. This work describes a manufacturing process to design and provide S^3 characteristics with the minimum variables to consider in its development.

Therefore, this chapter introduces the manufacturing processes not from the multidisciplinary topic or the fields that define it but from the vision of concurrent engineering and systems by placing it as a generic entity that allows studying its parts in a general manner to seek specific solutions to complex problems. In addition, the process of the raw material is presented in broad strokes to generate a final product. This representation allows studying the process the materials follow during the transformation in an isolated way to define what their design, redesign or update involves clearly.

3.1.1 Generic Model of a Manufacturing Process

According to the analysis of the most frequent topics in the manufacturing processes, variables are required to help determine the process's processing time, frequency, resources, and effectiveness. This representation is complex if one tries to include all the existing manufacturing processes; however, there are specific requirements that any manufacturing process performs. In other words, describing a manufacturing process can be done from the resources it uses to be carried out instead of its complexity.

A manufacturing process refers to the transformation processes executed on the raw material to generate components with added value. A generic model of the manufacturing process can assist and summarize your design to identify areas of opportunity by using the implemented attributes of the S^3 concept. Observing the existing manufacturing processes (Benedict, 2017; Klocke & Kuchle, 2009; Robert H Todd, Allen, & Alting, 1994), all of them require parameters to be carried out in the manufacturing lines to carry out the transformation of the raw material. The model that describes these parameters is presented in Figure 3-2.

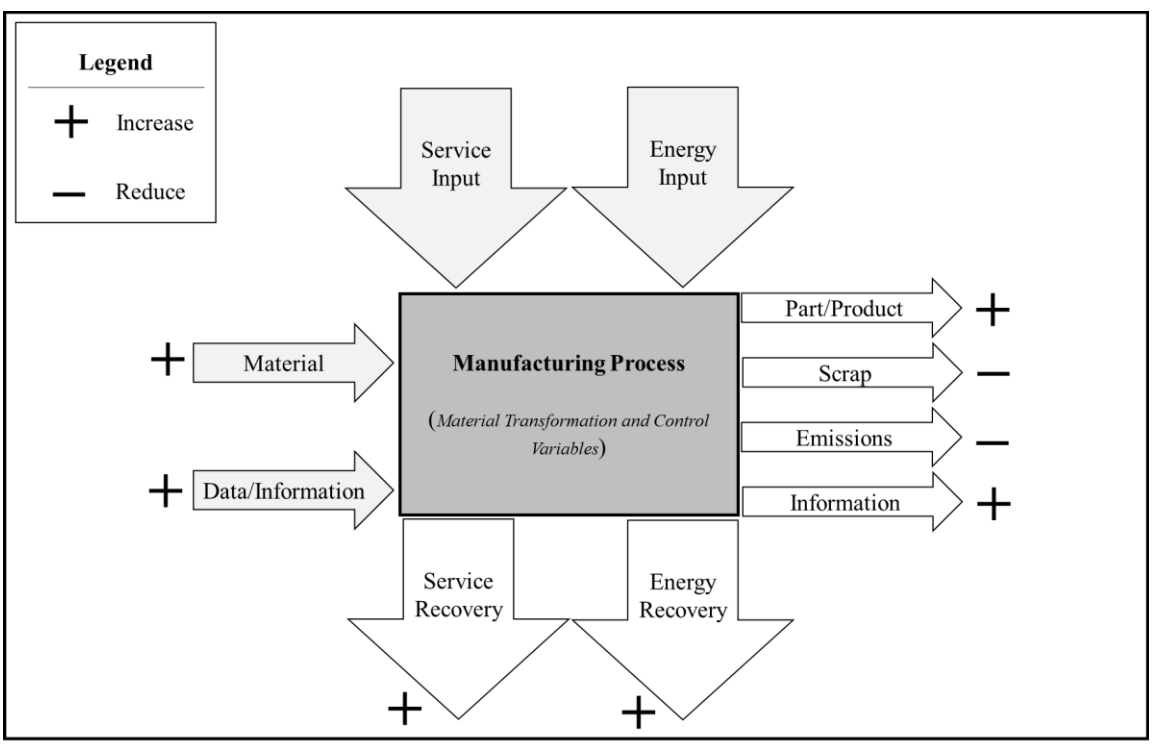

Figure 3-2 Generic model of manufacturing processes

It is important to note that in a manufacturing process the increase in material and data / information aims to carry out the transformation process maximizing the use of material, so that, in the first instance, more parts / products would be obtained, and the quantity generated of scrap would be reduced. Additionally, with the appropriate selection of transformation processes together with sensing and automation solutions, the aim is to reduce the amount of emissions produced, maximize the amount of process information to share it with previous or subsequent processes. Likewise, auxiliary services and energy are used to carry out the transformation process, in this way, the instrumentation would help to measure these inputs in order to recover part of them. Therefore, the figure represents the general objectives of each of the inputs and outputs as points to increase or decrease in a manufacturing process. The generic model of the manufacturing process is detailed below.

The manufacturing processes require raw material; this is represented in the model as i) Material since it does not necessarily have to be a new component or raw material in the production lines. It can be a list of elements, previous assemblies, metals, ceramics and even assembly material necessary to carry out the joining of parts, ii) Data / Information refers to the essential parameters that must be transferred to the manufacturing process to carry out the transformation process, this parameter It encompasses the mathematics of the process, the physical and chemical phenomena of the part and the dimensions that must be introduced to carry out the transformation successfully. Usually, this information is compiled in a manufacturing order that contains the final specifications of the component in turn. iii) Service, the services constitute an essential part of the manufacturing processes since they maintain a static regime in the process variables. Refrigerants, gases, liquids, heaters, support materials, among others, correspond to usual services that can be used by manufacturing processes to provide stability to the material and that the process can be carried out correctly. iv) Energy, as its name indicates, is the driving force necessary to carry out the transformation of the material. In traditional manual processes, this energy may be in the force that the craftsman executes to carry out specific tasks. In an automated process, the driving force that usually powers the process is electricity; however, the energy can come from various sources that help achieve the transformation process for specialised manufacturing processes. These four requirements of the generic model constitute the input of the manufacturing process, that is, the requirements necessary to execute it. However, six components can be observed in the output, the output of the original four, the remainder of the material, and the combined action of energy, services, and material in the form of emissions. These refer to the following i) Part / Product is the result of the transformation process. It contains new characteristics described in ii) information that is part of the manufacturing order resulting from the previous process. The waste generated in the process has been included as iii) Scrap, which contains the shavings, dust, pieces or residues depending on the transformed material. On the other hand, iv) Emissions correspond to waste, usually as gases, resulting from the union of energy with the material and services. This combination usually causes the effects of the transformation of matter released from the material's surface into the environment. International manufacturing regulations have increased with the impact of these gases on the environment, so their measurement, capture, and purification are growing requirements for the industrial sector. v) Service Recovery implies the treatment and reuse of the services carried out in a manufacturing process. While vi) Energy Recovery does the same thing with the energy used in the transformation process.

In addition, the figure shows marks of increase and decrease. These marks are aligned with the ideality of the manufacturing systems and the needs they have. The ideal manufacturing system takes advantage of the unique resources to satisfy high volumes of customization in multiple production lines, in short periods, low individual costs and meeting the growing market. The manufacturing systems with the most significant extension in the industry correspond to Make to Order (MTO), Make to Stock (MTS), Assemble to Order (ATO), Assemble to Stock (ATS), Engineering to Order (ETO), Configure to Order (CTO) and Build to Order (BTO) models. Generally, these systems are associated with product customization, complexity when establishing production lines and volumes, design needs and interaction with suppliers. For an ideal manufacturing system, it should cover certain aspects following (Carbone, 2001): i) High level of customisation, ii) Customer-driven design, iii) Short cycle time, iv) Not volume restrictive, v) No inventory cost, vi) High supply integration and vii) Minimal production cost. Table 3-1 shows the list of characteristics of the most widespread manufacturing systems. Therefore, the manufacturing processes that constitute an ideal manufacturing system must increase the volume of production or material. The previous information must be accurate for the transformation, and services and energy must be recovered and reused. In a series of continuous processes, forming effective distribution networks, the products generated must be remarkable, the waste minimum, the emissions detected, collected, treated and minimized when they are expelled from the manufacturing process and the information with which it enters the processes subsequent sharing efficiently to increase the value of the product along the value chain.

Table 3-1 Characteristics of manufacturing systems.

Aspect	MTO	MTS	ATO	ATS	ETO	CTO	BTO	Ideal
Customisation	✪	○	◉	○	●	◉	✪	✪
Customer-driven design	○	○	○	○	●	◉	●	✪
Cycle time	◉	⭘	⭘	◉	●	⭘	⭘	⭘
Volume	◉	●	●	●	●	◉	●	✪
Inventory	⭘	●	◉	●	○	◉	○	○
Supply integration	○	○	◉	⭘	○	●	●	✪
Production cost	◉	⭘	⭘	○	●	◉	⭘	⭘

Legend ○***None*** ⭘***Low*** ◉***Medium*** ●***High*** ✪***Tailored***

The types of transformation processes dictate the purpose for which they are to be carried out. This also limits the study of the vast amount of manufacturing processes that exist and are being explored day by day. According to the physical mass exchange phenomena in the parts within a production line, three functions are involved. From the point of view of the material, according to (Groover, 2010), these can be listed as follows:

- To change physical properties.
- To reshape or resize pieces.
- To achieve dimensions and surface finishing among specific tolerances.

How Groover presents it may be too general for the public outside the manufacturing processes. However, going deeper into the categorical operation of the transformation processes, the definitions of (Khandelwal & Taneja, 2010), described in the same way what happens with the components, to be more descriptive from the physical and mass point of view:

- Mass-conserving processes. The mass of the workpiece is equal before and after the manufacturing processes to the raw material (e.g. injection moulding, extrusion, die casting).

- Mass-reducing processes. The mass of the workpiece is higher compared with the mass after manufacturing it from raw material. Removing material from the original workpiece is needed to achieve the geometry and shape desired (e.g. milling, drilling, turning)

- Mass-adding processes. The workpiece is joined permanently with another. Joining processes are commonly achieved after all pieces are treated individually (e.g. welding, assembly, 3D printing).

Nonetheless, in this category, the types of manufacturing processes can be analyzed depending on their nature, whether they have a mechanical, thermal or chemical intervention to obtain the desired forms or processes (Swift & Booker, 2003). Understanding the manufacturing processes also helps decide the control variables that can be measured and controlled to optimize the process (Ruotsalainen, Heinämäki, Guo, Laitinen, & Yliruusi, 2003). Thus, particular control variables for manufacturing processes depend on the type of process selected, e.g. plastic processing depends on temperature and pressure, sensors capable of measuring these magnitudes are needed to improve the manufacturing process or woodworking, which involves controlling humidity in the environment to avoid swelling (Tabarsa, Khanjanzadeh, & Pirayesh, 2011). Describing the nature of the manufacturing processes helps define the control variables involved in the transformation and the co-variables engaged so that the process is carried out in the best possible way. The central natures of manufacturing processes are listed below:

- Casting: This process involves a solid metal being melted and poured into a mould or cavity to adopt a new form. In this way, shapes with complex geometries and precise tolerances are obtained both on the outside and inside of the part.

- Plastic & composite processing: It is a process in which natural fibre is mixed with thermoplastic to generate pellets and produce new components or final products through injection, blowing or moulding processes.

- Imaging and coating: Image processes are aided by optical instruments to recreate an image in the surface it is applied to. On the other hand, the coating is assisted by thermal, chemical depositions to cover a surface and protect it from ambient.

- Moulding: This is the process of shaping raw material using a rigid frame. Usually, an original pattern or sculpture generates the negative with which the piece will be created.

- Forming: This is the approach of creating metallic components by deforming the metal but not by removing material of any kind. Die and punching tools are implemented.

- Machining: Consists of power-driven units to form or shape metals. The forming is done by removing extra materials from a workpiece. There are three types of machining according to the tools occupied in each: traditional, press and modern machining.

- Joining: This is the action of gathering different pieces to form a new part.

- Additive manufacturing: This is an approach that builds 3D objects by adding layer-upon-layer of material. This technology aims at rapid product realisation and personalised components.

- Non-Traditional processes (NTP): These processes gather novel materials, techniques and technology to form and shape different parts. Mechanical, Electrochemical, Chemical, Electro-thermal processes are NTP depending on the nature of energy used for material removal.

As shown in the generic model, the control variables are at the centre of the transformation process since they are the measurements that must be made to have control of the manufacturing process; understanding it, measuring it and processing that information helps to transform the material with the appropriate parameters, using the energy and relevant services for this purpose. In general, the common control variables are presented in Table 3-2 for the types of manufacturing identified.

Table 3-2 Common control variables for manufacturing processes.

Type of process	Control variables
Casting	• Temperature • The temperature of the water-cooling jacket • Flow of material
Plastic & composite	• Temperature • Pressure • Plastic granules • Drill motion
Imaging and coating	• Light reflection • Temperature • Agitation • Air flow • Air pressure
Moulding	• Charge of material • Drill motion • Holding time • Cooling time
Forming	• Pressure • Vibration • Shear force
Machining	• Spindle speed • Rotation speed • Depth
Joining	• Flux coating • Voltage • Temperature • Endurance • Blend
Additive manufacturing	• Temperature • Viscosity • Flow • Distance of nozzle
Non-traditional processes	• Temperature • Ph • High pressure • Fluid supply • Lamp intensity • Voltage

3.1.2 From raw materials to final products

A manufacturing process is a set of activities to be carried out in a machinery inside a manufacturing facility. Its objective is to transform materials to increase their value, form them, assemble them and give them post-processing to generate final products delivered to the customer. However, the design of a process is centred on the development of products and their properties, material, mass, density, shape, functional features, dimensions, tolerance, and surface finish.

The manufacturing process depends on the resources available (Barney, 1991). Among others, material, machines, human, capital and information resources are needed to define the process of converting raw materials into added-value products (Guerras-Martín & López, 2015). To develop a manufacturing process, it is crucial to consider the four phases of the process development, identify the characteristics of the product entity offered and write down the attributes with different alternatives to cover them. Resulting in the following steps:

1. Determine the process inputs.
2. Identify by its activity the type of manufacturing process to design.
3. Identify by its function the steps needed to accomplish the product to be developed.
4. Determine the process outputs.

It is essential to address challenges in the manufacturing process development process. Every manufacturing process development involves at least three phases: *i)* a preparation phase to determine the process inputs, reception of components, quality check or distribution along the processing line is considered in this phase to design distributed and functional manufacturing cells; *ii)* a forming phase to manufacturing goods covering the design requirements, functions needed for the production of individual parts are considered with machinery and tools to form the manufacturing pieces and; *iii)* a post-treatment phase where outputs are produced effectively, subassemblies, finishing, coating, among others.

The process inputs are determined in earlier stages in conjunction with the functions that the product entity must cover. However, process development is highly influenced by the physical properties of the raw material selection and the volume to be produced during one period. Besides, process development pursues establishing a manufacturing process to cover the expectation of products and minimise the cost while increasing the production of the goods. Better design decisions result in better outcomes for customers and users, generating higher profits for manufacturing firms (R H Todd et al., 1994). Another criterion to influence the manufacturing process is the batch size, tolerance and finishing of the output. Thus, the manufacturing processes could be classified by their state of raw material, activity or function.

The state of raw material influences the consideration when selecting processes due to the machinery needed to process solid, liquid or gaseous materials. The state of raw material determines the activities and functions required to operate in optimal conditions for the manufacturing firm. The input and output elements of the presented list should include the specification when acquired and delivered. According to the material obtained as input, it is necessary to analyse, synthesize and evaluate alternatives in terms of cost, time and availability. Similarly, with the produced material or outputs of the manufacturing process, the engineering activities are related to process equipment, tooling and process steps.

For the author, the flow diagram for the development of a manufacturing process is defined in Figure 3-3. It shows the minimum characteristics necessary for the operation of a process, however simple it may be. i) Analyze the availability of inputs, generate a specification sheet for the type of ii) activity required, the volume and frequency of the product, iii) the primary activities to add value, both reduction and mass conservation, the machines together with the tooling and support parts, assembly or finishing activities and finally, the iv) outputs together with their specification sheet.

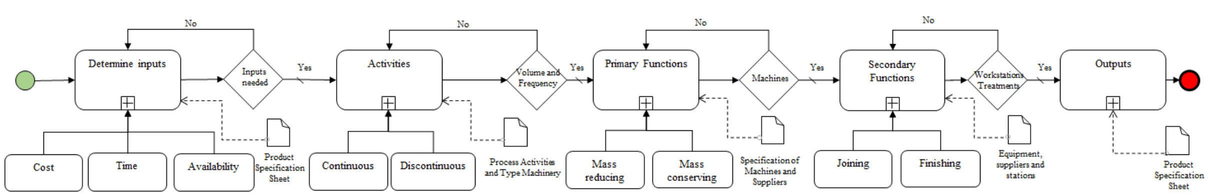

Figure 3-3 Manufacturing Process Development Flowchart

As can be seen, among each of the characteristics that must be carried out during the process, decision-making is shown represented by tollgates. Along with the process, development is expected different specification sheets. Product Specification sheet considers the evaluation of suppliers, components, availability and cost to the assessment of parts, time and availability of suppliers. Process activities and types of manufacturing are related to the volume needed to satisfy the demand. Specification of machinery is then expected with the volume determined to search for machinery, tooling and suppliers to cover the order. Mass-reducing or conserving activities are then specified to shape the material, tolerance and mass should be achieved by the selected machines. Equipment, suppliers and stations are evaluated for a secondary process where joining and finishing of the product takes place. Finally, a product specification sheet as output is expected to satisfy the anticipated solutions from it.

In the literature, the manufacturing processes are determined by the products; however, understanding the development of manufacturing processes can contribute to the creation of methodologies for their development, updating or increasing characteristics that make them more efficient. On the one hand, the IPPMD RF contributes to developing methods for creating entities in the industrial environment. On the other hand, the generic model of manufacturing processes emphasizes the most relevant attributes for the manufacturing sector, decision-makers objectives when describing a transformation process, and the types are also presented. Besides, primary manufacturing processes encompass countless industrial processes and their characteristics. By putting these ideas together, there is the development of an RF for manufacturing processes. This contributes to the lack of methodologies that allow the creation of manufacturing processes; however, the purpose of this redesign has to do with the primary objective that promotes the I4.0.

The promoted efforts have to do with using communication resources and the integration of decentralized systems for decision-making. The manufacturing processes that the industrial sector is looking for are the KDMP, for this, it is necessary to establish not only methodologies that promote the development of the process entity in an IMS but to establish how to exploit the S^3 characteristics of the system for its definition, design or redesign in an IMSy. These attributes in a manufacturing process will be described and used to define levels and activities to develop the S^3 Process RF.

Chapter 4 Sensing, Smart and Sustainable Process Development Reference Framework

As was introduced in the previous chapters, manufacturing has evolved since its arrival. The use of technologies has dictated the direction of the industry since its extension depends on the preparation of these spaces. Thus, the conjunction between educational institutions and companies has mainly been responsible for scientific discoveries, practices, methodologies, industrial applications and optimization of resources. This duo benefits from government institutions, decrees, laws, and investment proposals in research and development as a compliment. In this way, the triple helix takes on vital importance in the gradual development of nations. The industrial sector takes advantage of the technologies and discoveries of science; mainly, it seeks to convert raw material, give it value and obtain a profit from the exchange of goods with the end-user. However, this ideology and industrial objectives have been complemented in recent decades, given the urgency of the various phenomena that threaten the planet. The indifference of manufacturing firms, despite fostering an excessive increase in specific sectors, has had to be reformed. Multiple efforts have been made to achieve the Sustainable Development Goals (SDG) established by the United Nations (UN) (Fritz et al., 2019). These efforts are aimed at economic, social, environmental, resource and alliances growth within nations with individual values and objectives that must be particularized inside different organizations of the countries. Although they are not established laws, they are guidelines that governments must implement to promote sustained growth. The SDGs dictate how institutions charged with ongoing development should operate within nations. For this reason, it is essential to transfer these objectives to the primary part of the industrial sector, the manufacturing processes. Traditional manufacturing processes focus on the development of the product itself. However, to establish manufacturing processes that promote sustainable growth, not only for the organization but for the nation, it is necessary that international objectives be particularized within a methodology so that they can be implemented. This implementation that seeks resources to pursue a sustainable purpose has been established as the S^3 Process.

4.1 S^3 Process attributes

In recent years, Manufacturing Process Development (MPD) has been conceived as a strategy to offer a new generation of processes characterised to provide Sensing, Smart and Sustainable solutions. MPD is justified among manufacturing firms to increase production flexibility, incur rapidly into shifting markets, and cover existing demand with the available infrastructure. MPD aims to maintain a high level of productivity, optimise resources, and decrease processing time while decreasing the environmental impact. These efforts take the international SDGs by way of establishing them in the industrial sector. The result of implementing S^3 solutions in the MPDs has been named S^3 Processes. In these processes, it is sought to meet international objectives and take advantage of emerging technologies, new process currents, innovations in production lines, and general, take advantage of new knowledge but structuring it so that it is reproducible by future generations. Therefore, S^3 Processes must be developed considering at least the general structure of a transformation process, the material, information, services and energy while considering the control variables producing goods inside a manufacturing facility. Thus, it is necessary to provide new process design approaches taking advantage of emergent technologies, practices and tools with sustainable objectives.

4.1.1 Sensing in the manufacturing process

Sensing in a manufacturing process offers to measure changes as a primary function to control the transformational process's variables (mass reduction, mass addition or mass conservance) and being conscious about emission, energy, and services consumed during the operation. Solutions refer to the sensing system acquired by physical attributes variations through devices (sensors) or human senses. There are multiple attributes capable of measuring, such as presence, temperature, pressure, viscosity, movement, and flow. The primary function of these sensors is to detect events and measure changes against their initial value; once a variation is detected, actions must occur to respond and obtain a different response from the process. Data collected is processed, and the subsystem exchanges an output with different values to get a reaction from an actuator (Hinger et al., 2018). Sensing processes often provide information as input to other systems. Typical applications for sensing methods are optimisation, system distribution (Ouyang et al., 2019) and monitoring through the process (Izawa, Ulmer, Staerz, Weimar, & Barsan, 2019). Data should be collected from different sources related to:

1. Material. The entrance of raw material at the transformational process that is occurring.
2. Production. Products or parts are generated from the manufacturing process at a defined time lapse. It is referred to the volume and budget designated for the product.
3. Scrap. Waste of material generated from the transformational process. Usually, the lower the scrap, the better the process is. The correct selection of material, machinery and tools reduces these material remnants, obtaining a positive economic and sustainable impact.
4. Information. That describes the initial state of the component that enters the manufacturing process, such as that which corroborates that the parameters defined between processes were executed.
5. Emissions. Collected as greenhouse gases in materials on which the manufacturing process is carried out.
6. Services. Consumption and collection of the flow, material or component used within the manufacturing process that helps the transformation.
7. Energy. Consumption and collection of energy used to carry out the manufacturing process.

The amount of data available would increment with the level of sensing that a manufacturing process has. Nonetheless, control variables are also to be perceived according to the type of process selected. Identify the type of process by its activity is determined mainly by the volume and demand. At the same time, its function defines the nature of the procedure determined by the raw materials' physical properties.

Thus, real-time decision making would improve consistently by the sensing solutions implemented. Sensing systems have enabled the automation of different processes inside manufacturing firms. Due to technology evolution and recent advances in nanoscience (Snelders, Valega Mackenzie, Boersma, & Peeters, 2016), there are efforts to improve the sensing systems and minimise their size (Camuffo, 2018); it has caused the implementation of novel materials and new forms of including sensors, especially in manufacturing with extreme working conditions (Lucia, Jr, Frazatto, Piazzetta, & Gobbi, 2014). Furthermore, there is ongoing work to provide methods that allow different techniques and arrays to produce accurate data (Al-Obeidat, Spencer, & Alfandi, 2020). Data processed and acquired from sensor outputs will enable the decision-making process (Rajagopal, Rathinasamy, Bhanumathi, & Krishnan, 2019). Thus, the accuracy of novel sensors is expected, and efforts on producing them is a common theme inside manufacturing sectors.

The manufacturing sector has opportunity areas that could be improved with the use of information. It is not limited to close environments but also open spaces and even between different supply chain actors. Thus, the importance of sensing solutions is reflected.

The minimal capacity to ensure the migration from traditional manufacturing processes into KDMP is the sensors. Sensors are the base for any intelligent system as they collect data for decision-making. In this manner, sensors provide context awareness, reflecting what is occurring in the manufacturing process. They are used to measure different magnitudes at a large amount of data. In a manufacturing process, some factors are needed to make decisions at various stages of the process. There are factors related to the manufacturing process itself, such as vibration, temperature or energy consumption, the status of the raw material such as presence, weight, flow or volume, and productivity variables such as quality, rejected pieces, or capability of production. Therefore, multiple sensors could be adapted to form a network that helps monitor different subprocesses of the system, thus, achieving a better understanding of the process and enables monitoring of a complex system.

This feature guarantees reliability and usability of information (Barbu & Militaru, 2019), where advances have shown digital and virtual sensors (Jin, Shui, & Shpitalni, 2019), sensor-less or self-sensing methods (Kakinuma & Nagakari, 2017), even the presence or movement where there is no sensor in electrical context (Kakinuma & Kamigochi, 2012). Monitoring activities depend highly on the quality of data and frequency of acquisition. On the one hand, reliability guarantees the integrity of data to make decisions; on the other hand, usability prioritises the variables to sense and keep monitoring during the system's operation, representing an investment of equipment and conditioning during the development or selection of the system.

It is sensing which aids in automating production lines to measure what occurs inside the manufacturing firms. Thus, the idea of detecting problems or predicting the system's behaviour before an event arose. The third industrial revolution was characterized by the decentralized approach and use of technologies; however, thanks to these technological bases, with the infrastructure of Information and Communication Technologies (ICT), making use of the Internet of Things (IoT) and emergent technologies to foresee events (Kashyap, 2019). With the analysis of statistics, historical information, and computing capacity, it is possible to foresee scenarios, recognise patterns, and emit judgements with techniques such as Convolutional Neural Networks, Recursive Neural Networks, and Deep Learning. Thus, predict the behaviour of the system for its correct functioning and detect problems during operation. Decisions emitted by the system depend not only on the sensors but also on processing capacity and sharing information. KDMP could not be achieved without data nor processing capabilities. Therefore, a Sensing solution is to be coupled with intelligent or Smart solutions, described in Section 4.1.2.

4.1.1.1 Sensing solutions in manufacturing processes

There exist not only physical or digital sensors; emergent technologies use sensor-less or self-sensing methods (Kakinuma & Nagakari, 2017). Statistics have proven the estimation as a feasible alternative when using electrical parameters. Thus, position, presence or movement can be sensed even there is no sensor in this electrical context (Kakinuma & Kamigochi, 2012).

Trends in sensors are related to virtual sensing (Jin et al., 2019), which have relevance since they are included in most ICTs. These types of sensors use analytical or empirical techniques. The former calculates the relationship of quantity against measurement parameters and is often implemented through data validation and reconciliation methods. The latter compares and estimate values against historical data of the same amount. These sensors are used to provide economical and practical alternatives against traditional instruments.

There are alternatives when designing a manufacturing process. However, it all depends on the implementation, conditions for its use and level of automation that it should contemplate inside a manufacturing firm. Table 4-1 shows the classification of the main sensors used in manufacturing processes.

Table 4-1 Classification of sensors used in Sensing Processes

Classification	Type of sensors	Magnitude
Contribution of energy	▪ **Active** ▪ **Passive**	
Way of operation	▪ **Deflection** ▪ **Comparison**	
Type of signal	▪ **Digital** ▪ **Analog**	
Number of storage elements	▪ **First-order** ▪ **Second-order** ▪ **Superior order**	
By Typology	▪ **Primary**	▪ **Length** ▪ **Temperature** ▪ **Pressure** ▪ **Flux** ▪ **Flow** ▪ **Level** ▪ **Optical**
	▪ **Resistive**	▪ **Potentiometers** ▪ **Thermistors** ▪ **Strain gauges** ▪ **Magnetoresistance** ▪ **Photoresist** ▪ **Electromagnetics**

Implementing a sensing solution for a process depends on many factors. The decision must be made by analysing the requirements and limitations that the manufacturing process has. Table 4-2 shows some of the criteria to be considered before acquiring a sensing solution. There are classified according to i) sensor characteristics, ii) installation place, and iii) economic factors.

Table 4-2 Important factors to consider when selecting sensors

Factors	Characteristics
Type of material	▪ **Solid** ▪ **Liquid** ▪ **Gaseous**
Physical properties	▪ **Roughness** ▪ **Finish** ▪ **Shape** ▪ **Form**
Composition	▪ **Metal** ▪ **Ferrous** ▪ **Non-metallic**
Distance	▪ **Embedded** ▪ **In contact** ▪ **Short** ▪ **Long**
Environment	▪ **Light** ▪ **Corrosion** ▪ **Encapsulated** ▪ **Safety and hygiene standards**

These solutions above are adopted to have sensed processes, which have the characteristic of measuring the factors described in the generic model of the manufacturing process. The sensor is a transducer that allows to analyse the change of magnitude and convert it into a voltage that some other unit will process. Sensing processes are necessary to gather available information directly from the process, transform the magnitude into signals that Smart solutions can process, and obtain knowledge of the system during the manufacturing process. Thus, a sensing process must be integrated into a process development flowchart containing sensing solutions to collect information in different parts. During the three phases or process development, there should cover the sensing solutions to transform physical magnitudes into signals and send them to a processor. Sensing processes aid in the automation of manufacturing lines. These solutions are more extended in KDMP that eventually derive in IMSy; sensing processes are required to make real-time decisions inside a manufacturing firm.

4.1.2 Smartness in the manufacturing process

The concept of Smart arises from the capacity of a manufacturing process to analyse and communicate information with both internal and external agents. The way the processor does it endows it with a quality that resembles tasks that human beings can perform, and hence they are called intelligent features. In the industrial context, Smart capacity is related to intelligence and reflects some capabilities that human beings can accomplish using rational abilities. This intellectual capacity came to play when modules started to reflect some of the primary activities that humans could do unconsciously. Even there was an emulation of some tasks, processing modules were only able to execute orders when applying mathematics into computer sciences. However, emergent technologies took that processing capacity and coupled with the signals processed by sensors; Smart modules became more efficient while processing information and making decisions to maintain a range where they were previously set.

The Smart modules have become more complex in terms of the amount of information they can process and the time they execute the orders they were programmed to. There is local data processing, that is, statistical routines are run on the data that has been collected throughout the operation or distributed processing that takes advantage of data processing in the cloud. CC aims at spreading the subsystems inside a manufacturing firm while BD analytics is up for processing a large amount of information. Nowadays, they are equipped with advanced algorithms that process information and compare it in real-time to make more efficient decisions while the process still going.

The amount of data processed would increase the time and quality of decision-making to optimise resources in the material process, reduce scrap while decreasing the resources and time needed to produce parts/products, and be aware of the variables that provoke the emissions, among others. The installed capacity in terms of processing would improve the time needed to process information and decide in shorter periods. Another improvement available in the market is connectivity. Smart modules can process data in real-time and share it with another module to monitor what is going on inside a manufacturing firm. This type of communication could be wired or wireless. It makes usage of the IIoT distributed along the shopping floor to process and display data, alarms or signals for all users. It could transmit information in different ways with the channels of machine-machine, human-machine, human-human.

Smartness is aided by novel techniques to perceive, process, learn, emit judgements and decide according to multivariable scenarios (Romero, Guédria, Panetto, & Barafort, 2020)(HALIT Eren, 2016). Smartness is exceptionally functional while processing historical data or forecasting events (Randhawa & Kumar, 2017), but integrating horizontal and vertical information makes it a valuable feature among firms (Panetto & Molina, 2008). Data processing techniques have been developed for a few decades. However, programming, routine efficiency, but above all, computational power have made these solutions affordable for manufacturing. Information processing techniques mostly derive from statistical science. Nevertheless, cloud computation generated findings that were decisive for processing large volumes of data in increasingly shorter periods. The combination of these sciences led to AI. Some techniques that have become increasingly important to fulfil this purpose are Genetic Algorithms (GA), Artificial Neural Networks (ANN), Artificial Organic Networks (AON), Convolutional Neural Networks (CNN), Fuzzy Logic, Deep Learning (DL) (Ponce-Espinosa, Ponce-Cruz, & Molina, 2014)(Ponce-Cruz, Molina, & MacCleery, 2016). Trends allow the modularity and flexibility in novel manufacturing structures, decentralising information but processing multiple area information to optimise materials and satisfy the demand.

Smartness is reached aided by novel techniques. The Smart solution complements the sensors as it is conceived for processing data collected, classifying it, and making a decision based on automated reasoning considering above the manufacturing process, the environment variables. The system is equipped with capabilities to perceive, process, learn, emit judgements and decide according to multiple situations studied in data gathered. Thus, the last characteristic achieved by Smart solutions is the system's adaptability, enhanced by having reconfiguration considered during the manufacturing design. A system with this characteristic should be robust capable of adapting a wide range of operations based on data (Kaleka & Morgan, 2017)(Adler & Dagli, 2012).

Both the Sensors and the Smart processing and communication units are the basis for generating KDMP. Within the concepts of I4.0, some pillars dictate the use of emerging technologies that allow the exchange and real-time monitoring of operations. Therefore, these two solutions are intended to bring traditional manufacturing to an IMSy. Although these solutions allow entry to what I4.0 is looking for, it is necessary to consider the new world currents, especially the SDGs. These objectives are intended to bring the sustained development of nations through the various entities that generate the economy in geographic spaces. They comprise particular standards for the industry, resource consciousness, better social conditions for the community and the workforce. With this, they have long-term sustainable objectives. That is why these solutions must be complemented with sustainable goals in economic, social and environmental aspects. This solution is included in the third S^3 characteristic and will be described as the sustainable attribute of a manufacturing process.

4.1.2.1 Smart solutions in manufacturing processes

Smart processes bring together the concepts of KDMP to migrate from traditional to IMSy. These processes make efficient use of the resources of manufacturing firms, especially knowledge, historical data and forecasting of events to prevent abnormal situations. This information is obtained from the processing units and is also used to feed various contiguous systems or departments from different areas that influence the production process. Its application has been extended to a greater or lesser scale within any size of company for decision making.

The Smart capability of a manufacturing process is made up of three basic qualifications *i)* the manufacturing process is learning and being able to make decisions based on past events or data projection; *ii)* ICT infrastructure are used to make the process more efficient, but at the same time resilient and; *iii)* manufacturing process is gaining new awareness of internal and external information that affects the system. Figure 4-1 shows the capabilities that describe a smart module of a manufacturing process (Randhawa & Kumar, 2017).

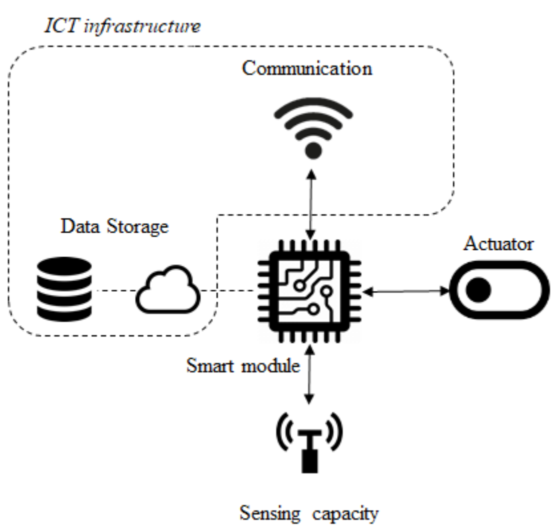

Figure 4-1 Smartness architecture

Considering what is exposed in (Halit Eren, 2018), intelligent process modules are situated along the four stages of the process development flowchart. Smartness is inherited when the process is equipped with the following three features: *i)* smart module, which is a system capable of processing data, *ii)* physical or virtual components, responsible for providing energy to the smart module to carry out the three capabilities above and *iii)* communication components, connected through ICTs protocols that allow the information sharing. Figure 4-2 shows the diagram of a manufacturing process that contains a smart module. The decision is executed with an actuator that in turn modifies the operation and triggers another manufacturing process.

See Figure 3.9. Table 3.7 sums up some of the features available for smart processes. It presents an automated process through local controllers integrated into a distributed control manufacturing process.

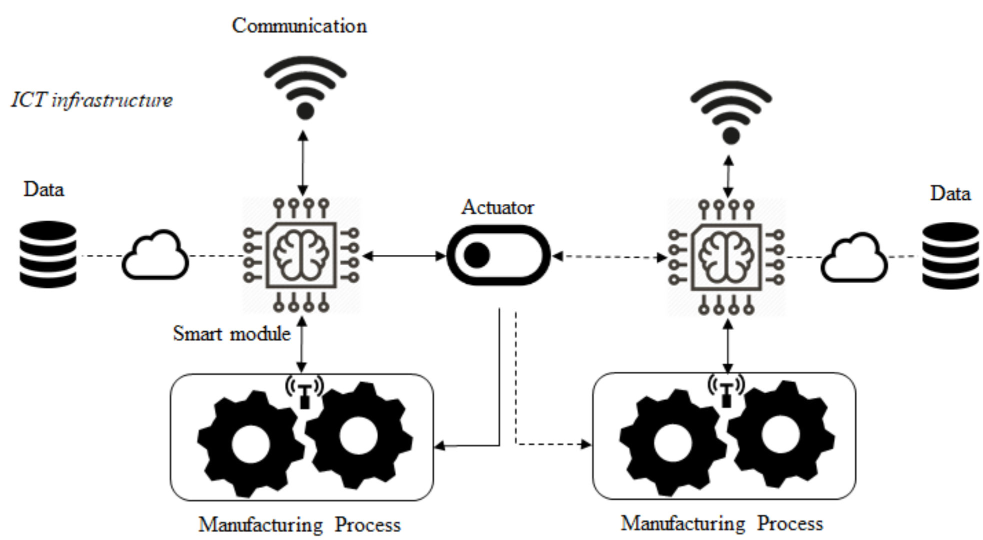

Figure 4-2 Capabilities of a Smart manufacturing process

The extension of this solution is due to the need to collect information, from products to manufacturing systems. This solution is of utmost importance since it allows automation of repetitive tasks, information processing, and data sharing through communication infrastructure (Kurasova, Marcinkevicius, Medvedev, Rapecka, & Stefanovic, 2014). The processing systems range from a signal or alarm that the sensor can measure to the decentralized process for large volumes of information in the cloud, taking advantage of BD computing services and solutions (Cloud, 2011). The features that integrate the processing modules and provide the manufacturing process with processing solutions and data sharing are not exclusive to any industrial sector and mostly depend on the context of the manufacturing process. However, some components can be located in the industry repeatedly. Those solutions are listed in Table 4-3 are mainly used in the industry. Which roughly describes the physical structure of the module, the components that make up the processing units and the communication technology that they integrate to communicate with other units.

Table 4-3 Features for smart components in manufacturing processes.

Feature	Characteristics
Structure	**Physical:** e.g. Mechanical structures, crystallines, ceramics.
	Based on electrical/electronic parts: e.g. Piezoelectrics, pyroelectrics, electro and magnetostrictive, superconductors, electrostatic
	Materials: e.g. Quartz, Rochelle salt, ammonium phosphate, glass rubber, paraffin, lead zirconate titanate, barium titanate, lead niobate, polyvinylidene fluoride.
Components	**Control:** e.g. Feedback (closed loop control system), concurrent (multivariable real-time), predictive (dynamic modelling, nonlinear continuous systems) control
	Sensors: e.g. Accelerometers, pressure, force transducer, noise/acoustic, microphone, impact, orthogonal, temperature.
	Actuators: e.g. Precision manipulator, pressure generator, ink/fuel injection, displacement, ultrasonic motors, smart composite.
	Processors: e.g. FPGAs, CPUs, GPUs, VLSI, ASIC, PAL, microcontrollers
	Interface: e.g. HMI, OS, application for in-situ user, mobile applications, cloud-based platforms.
Communication	**Protocols:** e.g. Profibus DP, Profibus PA, Profibus FMS, Foundation Fieldbus HSE, LonWorks, Interbus, DeviceNet, HART, ASI, BITBUS
	Technologies: e.g. Wired (ethernet, USB, USB-C, Optical-fibre), Wireless (Wi-Fi, RFID, LTE, NFC, Bluetooth)

Trends in smart processes are related to the adoption of emergent technologies and the decentralisation of individual subsystems. Modularity and flexibility are to be implemented aided by practices of standardisation and ICTs infrastructure. S³ Process should be aware of the complete manufacturing process to optimise the materials needed to satisfy the demand.

Although the Sensing and Smart solutions allow the automation of manufacturing processes, it is required to have organizational objectives that determine the purposes during the characterization, development or updating of manufacturing processes. For this, the sustainability characteristics must be studied as designs or updates to maintain the manufacturing firm's sustainable growth. The third characteristic of the S^3 Process takes advantage of the sensors, the processing and the communication infrastructure to update the decisions based on the parameters established for the effective operation of the manufacturing processes.

4.1.3 Sustainability in the manufacturing process

The Sustainable concept in the manufacturing sector is related to the production of goods during the manufacturing process. The term sustainability in the industrial sector focuses not only on the environmental impact that the manufacturing process can have but also on the organizational objectives of a manufacturing firm, decision-making, long-term goals, and budget assigned to design or update processes. Therefore, the term sustainable usually refers to at least the following dimensions *i)* environment, *ii)* economy, and *iii)* social or equity (Godschalk, 2004), comprised of multi-dimensional attributes that allow it is efficient and ethical (Berke, 2002). Some other ideas emphasise the coherence of sustainable infrastructure with objectives, the importance of learning, innovation, and networks (Allwinkle & Cruickshank, 2011)(Brocke et al., 2009). In comparison, others highlight the importance of knowledge management in modern manufacturing processes (Garcia, 2007). Thus, the sustainable manufacturing process reinforces the ability of humanity to make and improve current development to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs (Lam & Yang, 2020).

In general, a sustainable manufacturing process can pursue three different motivations. In the literature, these reasons are found as E3, which precisely refer to the three dimensions that were previously mentioned. Therefore, sustainable solutions refer to installed capacity, together with organizational policies capable of transcending the manufacturing firm and impacting society, the economy or the environment. In this way, its transcendental objective must be focused on preserving the health and well-being of all those directly or indirectly involved.

In the case of the generic model of transformation processes, it has been chosen that these purposes be adapted to four motivations that do not lose sight of the dimensions but rather serve to particularize each of the essential aspects of the process. The motivations of an S^3 process related to the sustainable solutions are *i)* reducing waste of materials, *ii)* reducing emissions of greenhouse gases, *iii)* Reduce, Reuse and Recycle (R3) services and *iv)* R3 energy. All of them influence the way of generating value within the manufacturing firm (Schönborn et al., 2018). However, those involved can perceive it and affect a positive economic aspect in the medium and long term (Bezin, 2019). Thus, decreasing the exploitation of available resources in communities and contributing to the quality of life of the society (Hale, Legun, Campbell, & Carolan, 2019) and, mitigating the impact to the environment while producing in greener manners (Rasmi, Kazan, & Türkay, 2019). Techniques and tools such as Eco-design (Mandolini, Marconi, Rossi, Favi, & Germani, 2019), Design for the Environment (DFE), Sustainable Design aid designers with manufacturing development, then it allows evaluating sustainability indicators in the manufacturing processes (Peiris, Kulatunga, & Jinadasa, 2019).

The vision of manufacturing firms in the context of KDMP is complemented with sustainability. This comprehensive vision allows to maintain automation objectives during the operation of the manufacturing processes and maintain the organisation's objectives in productive matters. Furthermore, the primary goals are related to i) profitability, which means that productivity of the system is suitable, ii) better quality of life for those who are impacted by the manufacturing firm (Nee & Opper, 2012), and iii) capacity to restore resources to the environment. The production processes used by most industries have not achieved the desirable sustainability (Jonker & Harmsen, 2012). In fact, traditional industrial production is linked to environmental disruptions, such as global warming and pollution, and consumption of non-renewable resources (Eslami et al., 2019). The monitoring of four field variables aims to decrease levels of waste, services, energy, and emissions while improving the system's productivity, seeking sustainable production (Maxwell & Van der Vorst, 2003)(Ponce, Polasko, & Molina, 2019). Besides, Life-Cycle Assessment (LCA) is used to find better solutions in activities that integrate the manufacturing firm (Krishna, Manickam, Shah, & Davergave, 2017), such as raw material acquisition, process distribution (Harmsen, de Haan, & Swinkels, 2018), logistic channels, product usage, product end-life or greener processes (Weidema, Thrane, Christensen, Schmidt, & Løkke, 2008). Measuring the carbon footprint and the impact on the environment has become a central goal for welfare and raising awareness of what is being produced and consumed (Shamsuzzoha et al., 2016). Future must be conceived as a circular economy that allows connectivity and collaboration between manufacturing processes and the rest of entites that comprises the enterprise.

Sustainability has been adopted as the third solution to incorporate in KDMP as the basis for IMSy. The size of the organization does not limit its adoption; although it requires efforts and resources, an MSME can use the concepts to propose a long-term design of an S^3 Process to achieve automation of the manufacturing processes without losing the relevant organizational reasons in the medium or long term.

4.1.3.1 Sustainable solutions in manufacturing processes

Sustainable solutions constitute the most complex subsystem to evaluate within an S^3 Process due to the multidimensionality in which they must be assessed and the different efforts that can be dedicated according to the organizational strategy. In practice, LCA is used in the series of processes that constitute the creation, usage and end of life of a product. In this way, the impact that its elaboration produces can be observed. Similarly, in a transformation process, measurements can be occupied, provided that the object of study is limited to the design of the manufacturing process. It is a technique used for the design and redesign of entities, the integration with S^3 Processes is feasible by identifying the inventory which concerns the manufacturing processes. In Table 4-4, common impact categories and damage associated are exposed.

Table 4-4 Indicators in the Life Cycle Assessment

Damage Categories	Impact Categories	Indicators
Climate Change	Global Warming	Kg CO_2 eq.
Resources	Non-renewable energy	MJ Primary
	Mineral extraction	MJ Primary
Human Health	Carcinogens	Kg eq. C_2H_3Cl
	Non-carcinogens	Kg eq. C_2H_3Cl
	Respiratory Inorganics	Kg eq. PM 2.5
	Respiratory Organics	Kg eq. C_2H_4
	Ionizing Radiations	Eq Bq C-14
	Ozone Layer Depletion	Kg eq CFC-11
Ecosystem Quality	Aquatic Eco-toxicity	Kg eq TEG in water
	Terrestrial Eco-toxicity	Kg eq TEG in soil
	Terrestrial acidification + nutrification	Kg eq SO_2
	Land Occupation	m^2 org arable

The sustainable solutions in manufacturing processes are related to the benefits offered when using an S^3 Process. On the one hand, the benefits to the environment from the reduction of emissions, the use of material or the use of components that increase the useful life of the manufacturing processes. The economic impact when designing or redesigning a manufacturing process is affected by the time the process would be available and valuable, the material and, the social benefits in the workforce, community and client or customer. In Table 4-5, the guidelines of the instantiation of IPPMD methodology, considering the three sustainable aspects: *i)* environment, *ii)* economic and *iii)* society, related to process entity is presented.

Table 4-5 Guidelines for Sustainable Manufacturing Process Development

Stages	Guidelines
Individual components specification	• Define the scope of analysis for the manufacturing process - Environmental (e.g. select climate change and ecosystem quality categories and work in reducing the indicators associated) - Economic (e.g. select components of the manufacturing process and resource category that allow decentralisation, reconfiguration and flexibility, thus, increasing the productivity and profitability of the process) - Social (e.g. select human health category and work in reducing the indicators associated)
Process selection	• Evaluate alternatives with emergent solutions: - Processes must be from standard machinery available in the market. - Processes should be comprised of green technology that decreases the environmental impact. - Processes should be equipped with monitoring systems. - Processes should be multifunctional. - Processes should be able to be reconfigurable. - Processes should be comprised of renewable materials. • Compare the alternatives: - Analyse, synthesise and evaluate different options of processes according to volume, mass, shape, form, roughness finish specifications of the product to be developed - Select the most sustainable, economic and social positive impact process • Define process: - Optimise the process development workflow. - Define the process in function of the product attributes to be developed. - The manufacturing process should be logical, practical and continuous. - Select different suppliers for all the available options in the market. - Before the activities in terms of value-added to the product, they made all effort to optimise the ones that generate it. • Decomposition of the process: - Select modular and flexible configurations to create multiple products with the processes selected. - Select processes that allow continuity.
Manufacturing Process Plan	• Identify the critical inputs: - Minimise the scrap from the process. - Pursue productivity, demand and quality. - Take advantage of the sensing and smart solutions to determine the best period to claim for supplies. - Minimize the environmental, economic and social impact. • Identify key activities: - Identify your competitive advantage in terms of manufacturing processes. - Standardise the politics of processing materials. - Minimise the transport of individual pieces and subcontract the activities that don't generate value. - Minimise the number of assemblies. - Optimise human resources. • Identify critical outputs: - If the process doesn't allow the specifications required by the customer or user, evaluate to modify the processor subcontract a finishing process to complete the production volume.
Evaluation of Manufacturing Process Plan	• Test the process: - If possible, evaluate the process with experts. - Make simulation and practices of the process before applying it. - Pilot test of the manufacturing process. • Prepare an emergency route for any inconvenience.

Sensing and Smart solutions are associated with automation, while Sustainable solutions seek to keep the manufacturing firm on medium and long-term strategies. These solutions in a manufacturing process seek in the first place to describe the process according to its characteristics and to delve into development to make them more efficient in the long term. The strategies that are followed depend, on the one hand, on the resources of the organization but, above all, on the transmission of value and image with which the manufacturing firm wants to be recognized. This topic is deepened below before showing the taxonomy or levels at which these solutions can be implemented.

4.1.4 Usage of the S^3 Process concept

The S^3 Process concept emerged as an alternative to close the gap between designing processes starting from the product and developing them from manufacturing operations in organizations. It takes advantage of existing technologies, tools, and goals in the medium and long term to generate a beneficial structure in any organization. The solutions it seeks to implement, correspond to new trends and collect and generate information to automate. In this way, the method is intended to be generic so that its application is not limited to a particular industrial sector.

S^3 Process in the manufacturing firms refers to the functions and solutions offered when the process is equipped with S^3 features accomplished by sensors, information processing module, control and actuation. The decision-making processes are influenced by knowledge, but they pursue sustainable motives. Furthermore, The S^3 Process concept can i) characterise existing processes, ii) develop new manufacturing processes highly oriented to cover the concepts exposed or iii) redesign existing processes to improve some of the existing characteristics. The usage of this concept is described below:

i. **Characterising processes**. The S^3 Process concept contains the attributes that a manufacturing process can acquire with the manufacturing firm's sensing, smart and sustainable solutions. Then, the gathered information could be processed and lately used to improve the manufacturing process and the production of goods. KDMP are the base for the IMSy. Therefore, the S^3 Process is the link needed to connect tools, technologies and goals during the manufacturing process design. Processes that have acquired S^3 solutions are used to improve the system's productivity, detect discontinuity and pursue sustainable motives.

ii. **New process development**. The S^3 Process concept serves to identify the needed requirements for the manufacturing process. As it should consider the generic model's inputs, outputs and transformation process, it links the requirements of the processes with the optimal strategies available. It comprises sensing, smart and sustainable solutions to design manufacturing processes that aim for sustainable solutions and optimisation during product development as part of a manufacturing system. Thus, the S^3 Process is used to create and adopt S^3 solutions in new projects related to analysing and developing new manufacturing processes.

iii. **Redesign of manufacturing processes**. The S^3 Process concept allows to characterize a current manufacturing process, identify existing solutions that provide the process with specific solutions and analyze the expected objectives of the manufacturing process aligned with the organizational goals. In this way, the current operating base is taken into consideration and looks for solutions that allow you to increase your automation level or enable sustainable production over time. Designers should implement or modify the solutions according to the technology affordable for the purpose and motivation of the process improvements. Redesigning the manufacturing process with sensing, smart and sustainable solutions will result in a necessary process capable of providing information about the process, its behaviour, and the products processed on it. Manufacturing based on knowledge aid with the productivity of the manufacturing firm and optimises processing time to generate value and remain competitive in the shifting market.

S^3 Process concept aims at analysing the manufacturing process in terms of the solutions offered during operation. Designers should analyse the current processes design and search for novel processes according to the solutions proposed. In this manner, solutions would provide information related to the manufacturing operations, inputs, stages of manufacturing and outputs from it. This concept is also suitable for analysing the particular viewpoints of the S^3 solutions and orient manufacturing to accomplish specific objectives of the firm.

S^3 Processes are comprised of multiple parts that belong to different engineering disciplines. The sensing, smart and sustainable viewpoints coupled with the design of the manufacturing process should be accomplished by the collaborative work of a multidisciplinary team.

During the stages of selecting components and process selection is essential to cover the primary objectives of the sensing, smart and sustainable objectives for the process. Then, during the operation plan stage, the strategy to measure the indicators, additional samples and the time to collect data should be exposed. Finally, during the ramp-up production test, the ongoing process should be executed to see any inconveniences to correct from previous stages.

Actuators that execute and modify part of the process to make decisions but pursuing sustainable objectives since its definition. The S^3 Process concept offers S^3 solutions and should comprise components that enable data collection, processing, and sharing. A manufacturing process is described from the generic model. However, the architecture in each of its characteristics can be seen in Figure 4-3. This architecture is valid for any entity that adopts Sensado, Smart solutions and seeks sustainable objectives.

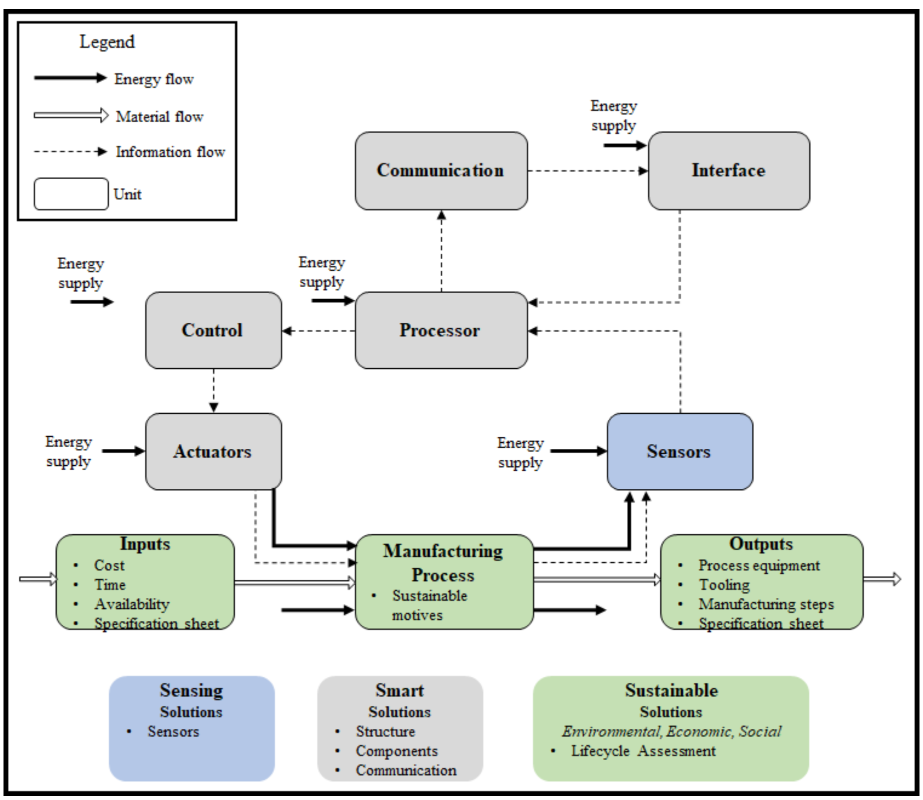

Figure 4-3 Architecture of an S^3 Process

The solutions implemented in the structure of an S^3 Process are *i)* Sensing, material specification, manufacturing parameters information, consumption of services, and energy consumption. Besides, control variables of transformation processes and output of materials generated part data, service and energy recovery. Additionally, products/parts, scrap, emissions and information along the manufacturing process monitor relevant information to make decisions. *ii)* Smart, modules comprised of digital or physical components and communication technology, they are in charge of processing the information compare it with a setpoint and modify through actuators to compensate and obtain the objective programmed, they can make decisions about programmed routines and alert abnormalities of manufacturing process functioning and, *iii)* Sustainable, organizational objectives, they should lead into reducing the environmental impact, increasing the productivity (if necessary), generating economic value and creating a positive impact for the society. The results of these solutions in a manufacturing process generate a process that is aware of the current state. Ideally, Figure 4-4 shows the schematic representation of what is involved in setting up Sensing and Smart solutions.

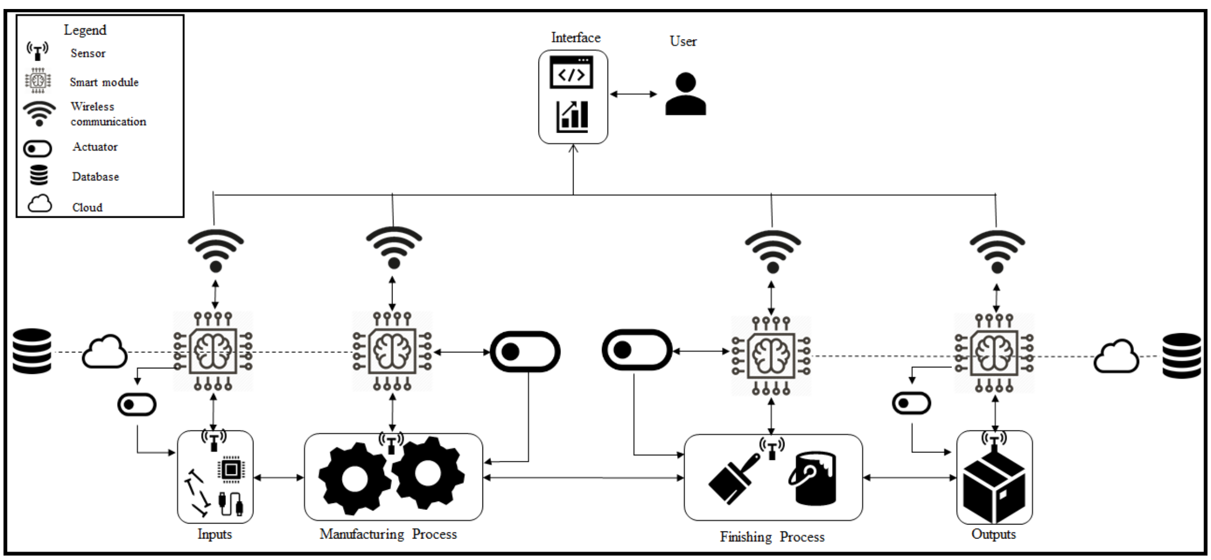

Figure 4-4 Schematic representation of an S^3 Process.

Using the S^3 Process concept allows characterizing a current transformation process (analysed as either mass adding, mass reduction or mass conserving manufacturing processes) and upgrading its characteristics to reach the organizational objectives. It would be complex both in time and resources to implement each of the processes that make up a manufacturing system; nonetheless, it is possible. Critical processes with greater relevance or that generate value for manufacturing firms require a particular interest in their development or updating. Thus, it is necessary to classify the current levels based on the solutions, tools or methods installed on the shopping floor. Hence the relevance of establishing levels that allow them to be defined.

4.2 Taxonomy

Manufacturing firms are migrating from traditional manufacturing processes to KDMP; they create Sensing and Smart processes that pursue economic motives and sustainable involvement of their customers and users in the designing process (Anning-Dorson, 2018)(Tuan, Rajendran, Rowley, & Khai, 2019). This phenomenon has been increased from the pillars raised in I4.0, emerging technologies, communications infrastructure and mainly, access to information consumption and production resources. Thus, gradually lowering the level of resilience at all social groups. Besides, the dynamics of society, social networks and a new type of consumer have generated that organizations expand technological resources as a means of communication throughout the value chain and with consumers to differentiate and exploit their competitive advantage in the marketplace (Porter, 2008)(Porter & Kramer, 2002). New practices and tools are adopted among manufacturing enterprises to offer innovative solutions, which also allow to analyse and evaluate the production of goods; new manufacturing types are based on knowledge and exploit data to satisfy the demand and forecast trends. Nowadays, manufacturing firms should be aware of their environment, competitors, and internal and external resources, centred on environmental and social impact. Manufacturing is the most important sector in terms of job creation and GDP among developing countries. The production of goods should pursue sustainable motives, not only in the products but also in the way they are produced. S^3 Process aims at covering sustainable reasons, taking advantage of the sensing and smart capabilities of the firm and evolving from traditional manufacturing into KDMP. The purpose of this work is to offer a methodology to carry out this process.

The reasons pursued by the I4.0 are aligned with the automation and creation of Smart Factories, Smart Enterprises and that the Product can feedback the production lines. However, it is really in the latter where the process of transformation and value addition of products occurs. This motivated the investigation of the manufacturing processes and construction of a reference framework that integrates the existing tools and practices to create S^3 Processes. In this manner, the same motives pursued by I4.0 are followed by the S^3 Process. This last concept seeks to be specific in achieving it and, therefore, an enabler of this migration. Thus, designers are guided into a systematic process that allows the design, characterisation and redesign of IMSys.

Because the S^3 Process is intended to be an enabler in this transition, it is necessary to establish the characteristics of the manufacturing process, both the current one and the one to be achieved. Different development scenarios will generate different solutions for the automation of manufacturing processes and the organizational reasons that drive investment. The analysis of these solutions can be grouped as a taxonomy, the purpose of which is to establish the technologies, practices, and tools for the solutions adopted in the entity's development. The levels of the S^3 solutions allow manufacturing processes developers to design clear objectives in the degree of action to be achieved with the manufacturing processes. Hence, the S^3 concept is implemented for characterizing the traditional and migrating to the new era of manufacturing firms.

The taxonomy users will be the developers of manufacturing processes whose need is present in section 4.1.4. Levels of Sensing, Smart and Sustainable processes are to be presented in this section. Developers need to identify the difference between processes features. Furthermore, aided by emergent technologies, manufacturing operations can be decentralised with the capacity to collect, process and share data, create networks with workstations and actors, and pursue sustainable objectives related to social, economic and environmental impact. Other solutions must be implemented when designing or redesigning manufacturing processes. Thus, multiple levels concerning S^3 solutions are described and the importance to consider them while designing manufacturing processes. Then an explanation of how to sense those variables is presented and how to control those variables using intelligent controls.

A taxonomy of the S^3 processes is presented to guide engineers in adding functionalities of Sensing, Smartness and Sustainability to manufacturing processes. For this, a description of the levels of each of the characteristics is required. In addition, the model for the construction of the S^3 Processes methodology is included, which is based on the IPPMD RF, followed by three case studies where the effectiveness to characterize and update manufacturing processes is demonstrated.

The three main uses of this taxonomy make it possible to highlight the objective of the research. In general, the taxonomy helps i) to characterize the current manufacturing process in a manufacturing firm, ii) to design a manufacturing process using the S3 concept and iii) to redesign a traditional manufacturing process to a KDMP. Its justification lies in the use and reduction of time for the new generation of designers.

4.2.1 Importance of defining a taxonomy of levels

S^3 Process has been used to link products and manufacturing system entities. It provides necessary information on how with the acquired technology, practices and tools primarily promoted by the I4.0 context, it is possible to migrate from a traditional to the IMSy. Besides, the S^3 Process concept uses the S^3 solutions to develop manufacturing processes where information is available from the raw material delivery to the shipping of finished products. The idea aims at increasing productivity, decreasing environmental impact and providing solutions that impact positively to society. However, the solution levels for the S^3 attributes are not defined for the manufacturing processes in the literature. Therefore, the relevance of this contribution in the industrial context. The lack of this definition has attracted investment in emerging technologies and not necessarily in their integration, which has led companies to be reluctant to adopt them due to the lack of short-term results, as might be expected(Mubarik et al., 2021)(Spieske & Birkel, 2021). Thus, the importance of defining a taxonomy is listed in the findings below:

A taxonomy will have its application in any of the following seven meanings. *i)* Improve processes to accomplish higher levels of automation through S^3 solutions. *ii)* Design novel processes that pursue sustainable objectives. *iii)* Develop flexible and reconfigurable manufacturing processes to extend their life and promote technology to identify where to improve the process during its operation. *iv)* Evoke the information and identify how to increase the autonomy of the process while pursuing sustainable objectives. *v)* Redesign processes according to the solutions exposed. *vi)* Improve a characteristic of the process to reach a desired level of automation and, *vii)* Make efficient decisions to improve the productivity of the manufacturing firm with the adopted solutions.

According to the literature review, an engineering analysis, the motives pursuit by the I4.0 context and the S^3 solutions exposed, taxonomy levels for the S^3 Process was defined identifying the existing functionalities available in the current market (Kaleka & Morgan, 2019)(Lacey, 2019). The levels of an S^3 Process are presented in the taxonomy shown in Figure 4-5.

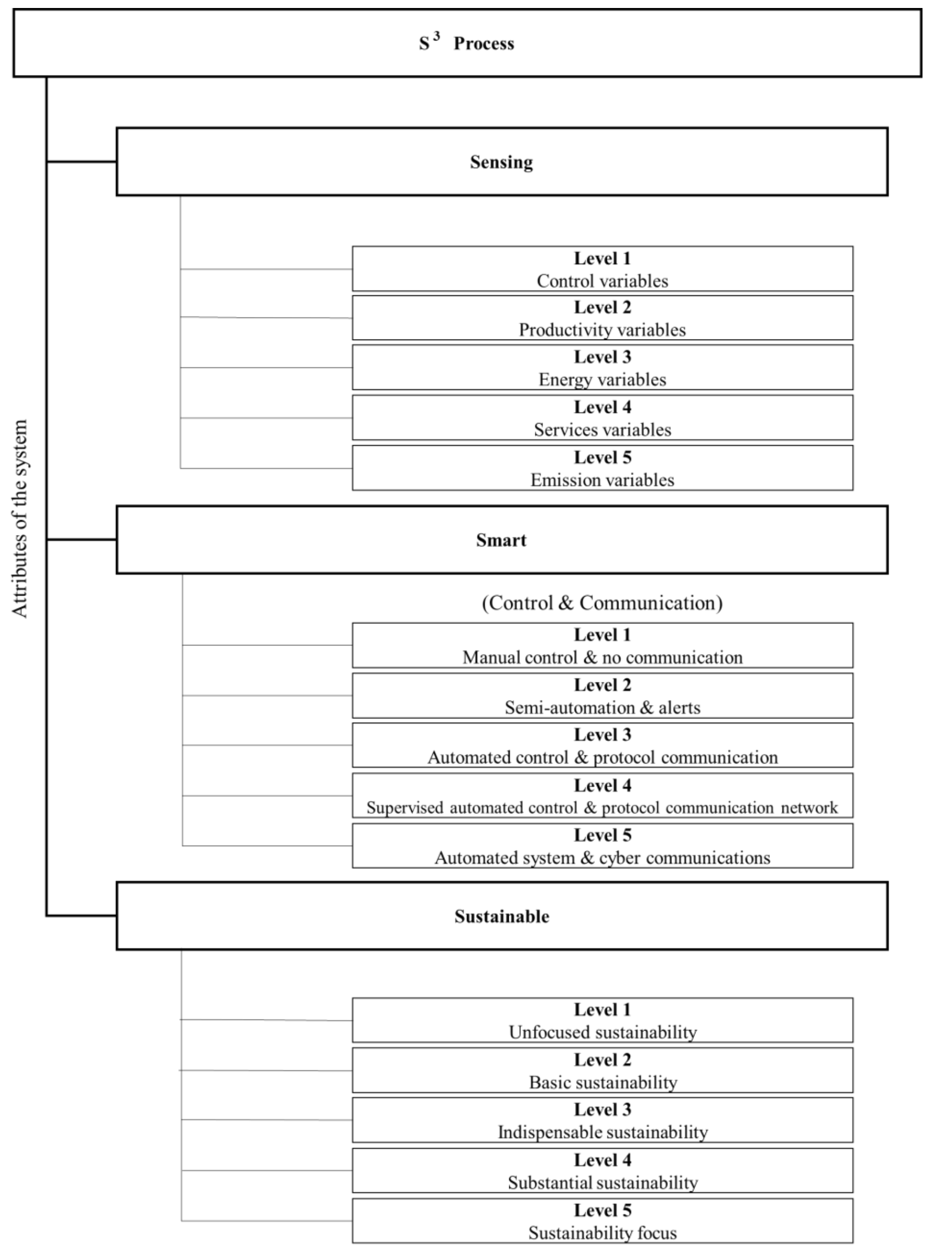

Figure 4-5 Taxonomy of S^3 Process.

The taxonomy presents levels one to five for each of the attributes. These levels are intended to be descriptive in how the feature is perceived in terms of its application within the manufacturing process. A guide for the use of the taxonomy is presented below.

4.2.2 Guidelines for the application of the Taxonomy

The taxonomy presents levels for each of the characteristics of an S^3 manufacturing process. The levels were determined according to their level of automation. Even a human solution would be defined as an intelligent system because they can consider every internal or external factor. Automation is pursuit by manufacturing firms to decrease human error, though. Due to this fact, levels were defined as follows: level one represents the lowest automation possible where human intervenes every time to gather and process information to make decisions, while level five means the highest automation solution available in the market. The intermedium levels are related to a certain level of automation according to S^3 solutions.

Each of the levels of the taxonomy represents a goal for Sensing, Smart and Sustainability solutions. The first two correspond to solutions to increase the automation of a manufacturing process, while the last is aligned with the long-term organizational objectives. The levels are cumulative; therefore, to achieve a level 3 in any of the attributes, levels 1 and 2 must have been previously covered.

The logic for defining these levels in the Sensing attribute corresponds to the relevance of the variables to be measured in a manufacturing process at an industrial level. In this way, the variables that determine that the transformation process is carried out correctly should be measured first, then the productivity variables, followed by the variables of the driving force that contributes to carrying out the transformation, the variables of the auxiliary services and finally the variables of the emissions generated during the manufacturing process. It can be seen that these variables meet the relevance, both of the manufacturing process and with the productive and economic objectives that are pursued within a manufacturing firm.

The Smart attribute implies the control of the manufacturing process and the communication or transmission of information with external agents (e.g. workforce) or with other workstations through their communication modules. As the Smart levels increase, the autonomy of the manufacturing process improves, both in the ability to automate tasks and the possibilities of transmitting information with various agents. As with the Sensing attribute, the levels are cumulative.

Finally, in the Sustainable attribute, the organisation's objectives are analyzed in three dimensions, economic, environmental and social. This attribute requires aligning organizational goals and allocating resources to controlling all the variables that make up the manufacturing process to increase the use of resources necessary during the transformation and reduce the waste of the variables that interfere, such as energy and services. and adequate control of emissions. Likewise, they are cumulative and require organizational efforts to adopt technology, investment of long-term resources, selection of materials for the development of more efficient manufacturing processes or migration to manufacturing processes with less impact.

The taxonomy presents the levels of each of the attributes. To use it, an organization's manufacturing process development team must define the automation and sustainability goals to be achieved. During the development of this work, three applications were limited, but it is not restrictive to them, in which the contributions could be applied. The guidelines for the use of taxonomy in each one are presented and described below.

i. **Design manufacturing processes with S^3 solutions based on a product**. An analysis of the industrial form of production of the product must be carried out, and the manufacturing processes that add value must be selected. Although any manufacturing process can be augmented with S^3 solutions, those that add value represent an investment opportunity for manufacturing firms. Therefore, the manufacturing process development team must select the processes in which the investment in S^3 solutions will be made and define the automation objectives of these, also, the variables that are going to be implemented, the relevant information that is convenient to share in previous or subsequent processes, define the control, how the information will be displayed or transmitted and finally the dimensions (economic, environmental or social) that are intended to be exploited from the investment in the manufacturing process. The objectives can be made from the description of the taxonomy, which will be presented later in this chapter, and thus define the level in each of the S^3 attributes.

ii. **Characterise existing manufacturing processes and improve their S3 attributes**. For this, it is necessary to identify each of the variables instrumented in the current manufacturing process, which is measured, what type of processing is carried out in the measurements obtained, how that information is communicated outside the manufacturing process, and the sustainable objectives the manufacturing process pursues, if they are merely productive or if they contribute to the organizational goals in the medium or long term. Once the levels of the S^3 solutions of the manufacturing process are identified, new automation objectives or the dimensions of the sustainability of the manufacturing process are defined, and the development team determines the levels that tie with those objectives using the taxonomy.

iii. **Selection of S^3 solutions in manufacturing processes**. Sometimes, there are manufacturing processes with a high degree of automation in which alternative solutions are required to create greater consistency in the responses of the devices. For this, a characterization of the current state of the manufacturing process is made. It is compared with the organisation's automation and sustainability objectives, and a new selection of existing solutions on the market is made. This type of analysis does not increase the levels of S^3 solutions. Its application is focused on rethinking the variables on which there are measurements, those that are not, and strategies to increase the perceived value of the investment in an industrial environment. This requires that the redesign team keep consistency issues in mind and conduct an in-depth analysis of the manufacturing process. This selection of S^3 solutions aims to answer variables of the most significant impact on the manufacturing process. The taxonomy is used to collate the attributes of the initial and final state of the manufacturing process and verify that the automation and sustainability objectives are achieved.

These guides were used in the development of the thesis work and the construction of the case studies. They are guides that emerged from the analysis and understanding of the activities that should be carried out in the characterization, design or redesign of manufacturing processes. The levels of the attributes will largely determine the type of physical solution, be it sensors, processing units or a variety of materials that must be acquired and implemented. Therefore, the description of the levels and their meanings within a transformation process are defined as follows.

4.2.3 Levels of Sensing solutions in S^3 Processes

The levels are used to pinpoint the current state based on the manufacturing structure according to a generic manufacturing process model. Being one the lowest level of automation and five the highest. The description of the levels and activities that occur in each of them are as follows:

Level 1 (Control variables). Only manufacturing process variables are monitored. There are instruments to collect data and identify abnormalities during manufacturing processing time. Typically, sensors are embedded in the process. The primary function is to detect irregularities of the current manufacturing process and send a signal to correct them manually. Typical process variables involve physical quantities such as temperature, pressure, presence, and refractive index.

Level 2 (Productivity variables). The manufacturing process is equipped with digital or analogue sensors to measure magnitudes related to productivity and scrap. Therefore, there is the monitoring of control variables. Productivity variables are generally expressed as a ratio of a physical magnitude and a unit of time (e.g., kg per hour, units per hour, pieces per minute). The sensing solutions at this level aim to maximise the production of components while reducing the amount of scrap.

Level 3 (Energy variables). The manufacturing process is equipped with multiple sensing systems to automate information and increase the productivity level of the manufacturing firm. Sensors can process a large amount of data and use the ICTs infrastructure, communicate with different modules through communication protocols and act in real-time with various technologies available. A micro phasor measurement unit (microPMU) is used for this purpose. It allows comparing the phase angle of the voltage at two different locations across a transmission line simultaneously. The primary function is to automate decisions based on the information collected regarding energy consumption.

Level 4 (Services variables). In manufacturing processes, it is crucial to monitor auxiliary services. For this, multiple sensors that allow the monitoring of specific variables of each service is used. Nonetheless, there is a variety of services available for different processes. These services are usually used by more than one process, so it is essential to be measured and controlled in real-time scenarios to acquire data from multiple sensors. Depending on the type of service used for the process, the variables to consider would be different, e.g., i) for coolers, flow, inlet temperature, outlet temperature, ii) for steam, initial pressure, absolute pressure. The sensing solution aims at maximising the use of services that could be shared with multiple manufacturing processes. Its function is to maximise its usage, recover the service consumed, treat it, and recycle it throughout manufacturing.

Level 5 (Emission variables). The manufacturing process is monitored by multiple sensors related to the emission of greenhouse gases. Measures such as the energy used per hour of the process are usually collected, the calories involved during the transformation, or in modern equipment, its equivalent in CO2 required, expressed as kg-eq of CO2. The control variables and product variables provide information that is gathered coupled with emission variables. The emissions gases are to be treated before exiting the factory. The leading sensing solution at this level is to reduce emission gases while maximising productivity.

Table 4-6 summarizes the attributes, technologies, and intervention levels of the workforce. Besides, the main characteristics of the levels are exposed to the importance of a process acquired with them.

Table 4-6 Levels of Sensing solutions for S^3 Process Development

Levels	Identification	Functioning	Intervention
Level 1	Control variables	• Embedded sensors. • Analogue and Digital • °C °F K. • Bar, PSI, Pa	The manufacturing process is equipped with sensors to regulate control variables only, referring to the variables of the particular operation (e.g. temperature, pressure, motion, among others). Thus, the manufacturing process is controlled during its execution.
Level 2	Productivity variables	• Multiple sensors • Analog and Digital sensors • Kg/h • Pcs/h	The manufacturing process is equipped with sensors to regulate its control variables and productivity of the process (e.g. presence, vibration, sheer force, among others). The quantity of material produced and scrap is regulated. Manufacturing processes aim at optimising them.
Level 3	Energy variables	• Energy management systems • Embedded sensors with processing data modules • Artificial Intelligence • KWh • Cal/h	The sensing system learns from historical data using multivariable functions; it makes decisions based on knowledge and current information about productivity and control variables. The system aims at autonomy regarding the main objectives of the manufacturing firms. Functioning of the station monitors energy consumption through Kwh or Cal/h occupied in the process.
Level 4	Services variables	• Multiple sensors • Flow sensors • Basic processing data modules. • Decision-making for valves • The temperature in and out • Pressure in and out • Flow in and out	The sensing system makes decisions based on measures derived from flow information of services, consumption and forecasting productivity of the station. Every manufacturing process at the industrial level is supported by a service monitored before and after being present in the manufacturing process. Depending on the service, different variables are observed (e.g. temperature in and out, pressure in and out, among others). The manufacturing process aims to gather information from consumers and recover a percentage of it during the sub-sequential operations.
Level 5	Emission variables	• Micro/nano sensors • Fusion sensor technique • Advanced processing data system • Real-time decision making for emission adjustments • kWh or Kg-eq CO_2 measurements	The manufacturing process aims at collecting information to reduce the emissions generated by the process. The manufacturing system makes the decision based on real-time measures. Estimation is commonly obtained with kWh measurements from the machines. The manufacturing process is highly influenced by the level of impact defined by stakeholders.

The level of these sensing solutions must be combined with the processing and communication that automate the manufacturing processes.

4.2.4 Levels of Smart solutions in S^3 Processes

Similarly to Sensing solutions, in the manufacturing processes, five levels allow knowing the degree of interaction in which the information is processed, but as a vital characteristic, how the information is shared either horizontally or vertically. They are organized from level one to level five, being the former the less and the latter the highest automated, respectively. They pinpoint the current state among firms and assist when upgrading to superior levels according to the system needs.

Level 1 (Manual control & no connection). Manufacturing process closed-loop control where operators make sensor interpretation and final decisions to execute actions. Operations are done according to specifications, and monitoring of production variables is prone to large variations. Besides, the manufacturing line is rigid (dedicated to one product), and low product variety is possible. Information is not collected nor analysed; at this point, humans are in direct control to correct irregularities and address management operations. In addition, communication language is usually continuous. The operator closes the loop by a manual operation. This operation causes fatigue, and the precise operation is not completed. If this closed–loop is transformed into an open-loop, the operator only receives the process results. Thus, the robustness and flexibility of the systems are extremely limited.

Level 2 (Semi-automation & basic connection). The manufacturing process is equipped with a control system that can achieve controlled variable requirements. However, the complete manufacturing operation could not be covered. Data is collected manually, and sensor information is interpreted based on established setpoints. The workforce still leads to manufacturing duties, but data collection feeds management levels to correct and improve production. Flexibility is envisioned but still complicated to achieve. Most of the information processing is made at manufacturing stations by humans aided by digital systems.

Level 3 (Automated control & protocol communication). Manufacturing lines are equipped with control systems to accomplish the controlled variable requirements (at least control, productivity and auxiliary services variables). However, the fundamental needs for quality control are not required. Flexible lines allow the production of different variants of the products and are achieved in short periods. Humans act at the supervisor level as most of the data collection is accomplished automatically. Basic automation allows increasing production minimizing production errors. At this level, smart modules are fed by multiple arrays of sensors capable of processing information, but humans still remotely manage significant changes.

Level 4 (Supervised automated control & protocol communication network). The manufacturing process is equipped with modules capable of processing a large amount of data and generating information based on historical data and predictive analysis; wireless and wired systems are interconnected. At this level, automated processes can make decisions and execute actions to improve the system's productivity. All the requirements of quality control are achieved. Flexibility is achieved thanks to the decentralized control system. However, a centralized control could be included; thus, many products can be manufactured in short times and large volumes. Intelligent processes provide the autonomy to recognize and execute routines for different scenarios. The communication language usually is discrete.

Level 5 (Automated system & cyber communications). The manufacturing process is equipped with decision-maker tree systems into the control module; the robustness and flexibility are high. The intelligent modules allow decentralized decision making and contribute to other subsystems to accomplish the purpose of the manufacturing firm. The quality control needs are achieved. Flexibility is performed based on reconfigurability or in multi-venue manufacturing strategies. Data is actively converted to weighted information as advanced hardware and software support the deployment of artificial intelligence to manage production. The human presence is reduced to the minimum just in punctual tasks as management is highly automated. Knowledge managed to manufacture not only base the decisions on historical data but also learn from previous experiences and are capable of making decisions based on the prior knowledge considering internal and external factors to maintain and improve the system's productivity.

Table 4-7 summarizes the attributes, technologies, and intervention levels of the workforce in each of the Smart solutions for a manufacturing process. The identification column describes the class in the manufacturing process, while the functioning generally describes the operation of the intelligent module. Besides, the main characteristics of the levels are exposed to the importance of a process acquired with them.

Table 4-7 Levels of Smart solutions for S^3 Process Development

Levels	Identification	Functioning	Intervention
Level 1	Human managed	• Human control	Human detects irregularities, process information and makes decisions while the connection between elements is inexistent. This decision making maintains basic levels of productivity in the manufacturing process.
Level 2	Semi-control managed	• Open-loop control system	Basic process and communication system, coupled with sensors, collect information and control. Communication is maintained at a basic level. The control system detects a variation in variables and executes a simple action. It makes use of set points as a reference.
Level 3	Control managed	• Closed-loop control system	A closed-loop system coupled with sensors collect, processes and send data to an actuator. This is achieved thanks to a more advanced communication protocol. There is a setpoint and feedback to modify different actuators in the system and accomplish the desired parameter in the manufacturing process.
Level 4	Automation managed	• Advanced control modules • Predictive analysis	Advanced capabilities modules make use of historical data to compare against recent information and make decisions to accomplish the desired scenario. Communication protocols allow interaction at various automation levels. There are multiple sensors and actuators interconnected to achieve value in the manufacturing process.
Level 5	Knowledge managed	• Artificial intelligence • Artificial neural networks • IIot	The advanced process with ubiquitous cyber communication module system processes data and learns from previous information. It targets a multivariable approach to find local and global optimums of the manufacturing process. The system is aware not only of its own capabilities but environmental information. The main objective is to maintain optimum levels on the system as a whole, based on productivity, quality and demand in real-time.

Both Sensing and Smart solutions allow the automation of the manufacturing process. This is a productive objective within the industrial context, which aims to reduce human error in the transformation processes and increase reproducibility. With this, tolerance ranges are concentrated in the production of components, and there is an increase in quality in the final products. However, the new manufacturing trends aim to increase flexibility and personalization of products for the customer or end-user. This has generated the decentralization of the manufacturing processes and hence the importance of joining these two concepts with medium and long-term objectives that allow the organisation's sustainability.

4.2.5 Levels of Sustainable solutions in S^3 Processes

The attribute of sustainability is the result of the vision of the manufacturing companies (Giannetti, Agostinho, Eras, Yang, & Almeida, 2020). In this manner, a KDMP will obey organizational objectives aligned to the described dimensions of sustainability. (U. Mishra, Wu, & Sarkar, 2020). This concept has been considered in at least three main dimensions: i) Economic, ii) Environmental, iii) Equity or Social. Furthermore, the primary goals are i) profitability, which means that productivity of the system is suitable, ii) better quality of life for those who are impacted by the manufacturing firm (Whittington, 2018), and iii) capacity to restore resources to the environment. Traditional industrial production is linked to environmental disruptions, such as global warming and pollution, and consumption of non-renewable resources (Eslami et al., 2019). The monitoring of the four field variables aims to decrease levels of waste, service, energy, and emissions while improving the system's productivity, seeking sustainable production (Eslami, Lezoche, Panetto, & Dassisti, 2021)(Tiwari, Sadeghi, & Eseonu, 2020). Nonetheless, the manufacturing processes used by most industries have not achieved desirable sustainability (Nara et al., 2021).

How sustainable levels tie in with manufacturing processes reflects the organization's leadership and long-term plans. Therefore, the levels of sustainability in the manufacturing process have to do with the joint effort to see it as a long-term growth strategy. Once the level has been pinpointed, plans ought to focus on a coordinated effort to generate well-being for those around the organization and clients.

Level 1 (Unfocused sustainability). The manufacturing process does not consider any sustainable aspect consciously, neither environmental nor economic nor social. Manufacturing process designers at this level are commonly familiar managed unconsciously of the potential that investing in sustainability could represent in their sectors. The manufacturing process is usually centred on the economic aspect to maintain operations in the market without long-term planning.

Level 2 (Basic sustainability). At this level, there are strategies mainly to remain active in the sector. Manufacturing processes consider sustainable objectives as a viable strategy. The designers of the process are formed with conscious integers that pursue an expansion of the current market. Manufacturing firms seek and complete the necessary level of sustainability norms to retain stakeholders along the supply chain. The primary function is to differentiate from the competitors.

Level 3 (Indispensable sustainability). The manufacturing process considers sustainable objectives, and there is an investment of being recognised among society. The designers are conscious of the efforts needed to compete in regional markets, accomplish norms to penetrate the culture, and expand operations. Manufacturing firms usually invest in more productive processes with a lower carbon footprint and generate an internal society image. The primary function is to maintain a medium-term vision while remaining competitive, taking advantage of the internal resources.

Level 4 (Substantial sustainability). The manufacturing process pursues sustainable objectives. There are efforts to invest in more than one damage category among the manufacturing system; sensing variables are commonly covered in the order presented. The designers of the manufacturing process are conscious of the impact generated by their resources and destine efforts to revert or prevent possible damage. The firms' strategy is published with the indicators selected, planning for future work and feedback about the actions carried out. Besides, there are efforts to generate a positive impact in at least three aspects, i) economic, ii) environmental, and iii) equity or social in either internal and external actors, including the supply chain. The primary function is to establish a long-term vision based on sustainability, remain competitive locally and expand to international markets with their mission.

Level 5 (Sustainability focus). The manufacturing process is focused on sustainability objectives, and there is a significant investment in multiple damage categories. The designers are aware of society's necessities and environmental needs and generate work opportunities to promote movement in the economy of a region. The strategy is recurrent, and multiple reports are exposed to previous, present and future work. There is continuous interaction with society to contribute to different projects for reverting the damage. Afterwards, the potential market recognises the firm's efforts to generate a positive impact in various fields. The primary function is to establish a long-term vision-oriented sustainability as the main differentiator among the manufacturing sector, remain competitive in global markets and generate a positive change around the world.

Table 4-8 summarizes the levels of sustainability. The identification column shows the general description of the level. Unlike Sensing and Smart solutions, the particular criterion is offered regarding the generic model of a manufacturing process and, finally, the intervention of the workforce in the process.

Table 4-8 Levels of Sustainable solutions for S^3 Process Development

Levels	Identification	Criteria	Intervention
Level 1	Unfocused sustainability	• Maintain operations in the market without long-term planning; processes are encouraged by production. This level considers: • Raw material produces scrap • Energy is wasted in the process. • Services are disposed of in nature when it exits the function. • Emissions of greenhouse gases are not considered during the design of the process.	Manufacturing process designers in this level are commonly unconscious of the potential that investing in sustainability could have. The main objective of the firm is to generate income to maintain operations.
Level 2	Basic sustainability	• Differentiate from the competitors and maintain operations, processes are encouraged by wealth and distribution. This level considers: • Processes are selected to reduce scrap in the raw material. • Energy is isolated in the process. • Service is used for different purposes before exiting the manufacturing process. • Emissions of greenhouse gases are detected during the design of the process.	The designers of the manufacturing process arose from the firm itself or consisted of technicians to understand the process at its basic level. The firm's main target is to reach more significant markets, offering an economic solving enterprise to the stakeholders and workforce.
Level 3	Indispensable sustainability	• Maintain a medium-term vision and remain competitive, taking advantage of the internal resources, processes are encouraged by law and communication. This level considers: • Processes are selected to minimise scrap in the raw material. • Energy is conserved isolated in the process to maximise its use. • Service is treated before exiting the manufacturing process. • Emissions of greenhouse gases are treated before leaving the process.	The designers are conscious of the efforts to compete in regional markets and accomplish norms to penetrate the culture. Steps of the manufacturing firm are not only oriented to expand the presence in the consumers' minds but to generate a significant impact on their public.
Level 4	Substantial sustainability	• Establish a long-term vision based on sustainability, remain competitive locally and expand to international markets with their mission, processes are encouraged by ethics. This level considers: • Scrap is reincorporated into the process. • Energy is recovered to use as the input of another process. There are green energy sources.	The designers recognise the impact of the brand on their public. There is adoption from the target markets. However, the relevant feature is that there are running efforts from the manufacturing firm to mitigate resource consumption. There is a

		• Service is treated and recycled before exiting the manufacturing process. • Emissions of greenhouse gases are minimised and treated before going through the process.	clear sustainable objective at mid-term or long-term to revert or prevent the negative impact on the environment. This generates a positive effect on the social or public image of the firm, increasing the acceptance of the market.
Level 5	Sustainability focus	• Establish a long-term vision focused on sustainability, remain competitive in global markets, and generate a positive change worldwide; processes are encouraged to preserve health, well-being, use renewable sources, and preserve the environment. This level considers: • There is no scrap during the process. Material is optimised. • Energy is recovered during the process and shared with other techniques. There are considered green energy sources as the main power supply. • Service is treated inside the factory to recycle in the process. • There are no emissions of greenhouse gases to the environment.	The manufacturing firm has established a long-term vision that involves the destination of resources to attend to social and environmental needs while offering work opportunities to promote movement in a region's economy.

As can be seen in the description of the sustainability levels, the primary objective lies in the input components that lie in the manufacturing process without losing sight of the central aim of the transformation process. For this, it is necessary to know in advance the operations executed in it and the critical variables that determine its function. In the case of criteria, each solution can be distinguished from the previous one or prioritized based on the promoted organizational objectives. It is known that a smaller firm will seek to prioritize economic effects over environmental or social ones. However, in the medium and long term, these objectives change depending on the organisation's development and the size it plans to achieve.

The S^3 Solutions taxonomy seek to establish what can be achieved at a certain level and raise awareness of current manufacturing processes. These levels serve as a guide to the minimum necessary to achieve automation and consider the generic model of a manufacturing process to measure inputs and obtain results that match long-term objectives. However, they are not an authoritative standard or regulation that responds to the specific context of the industrial sector. That is why the S^3 Process Development Reference Framework seeks to establish the activities to carry it out but not to define the organisation's objectives. This contextualization depends on who implements it. The following section describes how this RF was built and the activities that must be carried out for its implementation.

4.2.6 S^3 Scorecard

Since the purpose of the taxonomy is to establish levels of S^3 solutions and use them as both automation and sustainable design objectives, an evaluation of existing solutions and solutions implemented in the manufacturing processes is required at the end of their development. For this, a practical tool was generated based on individual characteristics of the solutions in each of the Sensing, Smart and Sustainable attributes of the manufacturing processes. Since it provides information on S^3 solutions and can contrast scenarios of increasing levels, it was called the S^3 Scorecard.

The tool's objective is to provide specific information on the physical solutions implemented and propose improvement actions if required to increase the level of the design of the S^3 manufacturing process.

This tool is radially mapped and uses five features from S^3 solutions. The characteristics were selected from experimental evaluations. In the assessment of manufacturing processes, it was observed that although it had undergone a redesign, the attribute level did not increase as the implemented solutions had done. This led to analyzing the physical components and discerning between the attributes that generate value as a solution from those that do not. In this way, even if a manufacturing process considers the implementation of multiple sensors on the same variable, it will not improve the overall value of the manufacturing process unless these sensors provide feedback on the value of the measure or contribute to developing information that can be used in previous or subsequent operations. Likewise, even if sensors are selected for the different relevant variables in the generic model, if they have a lower resolution, the Sensing value will not increase, although, in the first instance, it could be considered this way.

The taxonomy operated cumulatively; that is, the previous ones had to be covered in their entirety to reach a higher level. The design of manufacturing processes allows for global objectives and allocation of resources for their implementation. However, although they fulfil the task, many of the solutions on the market can do so to a greater or lesser extent depending on the precision required in the process. That is why the S^3 Scorecard individually evaluates the characteristics of the attributes (Sensing, Smart and Sustainable) of a manufacturing process. For each of the characteristics listed below, five values have been defined that can be acquired to compare and give precise recommendations on how to increase automation or sustainable objectives in different projects. The characteristics are listed below, and the logic behind the values they can take in an evaluation is described.

i. **Sensing**

a. **Quantity.** The number of sensors used to measure critical control variables (transformation process), productivity, energy, auxiliary services and emissions. It is considered quantity only those sensors that allow guaranteeing the measure's value utilizing arrays of sensors or through secondary variables that verify the value of the primary measure. The values defined were: Single sensor, array, replicated arrays, multiple replicated sensors, replicated configuration.

b. **Type.** Type of sensor used, whether of status such as no signal sensor, passive analogue, active analogue, digital or virtual assets, their inclusion increases the attribute's value as this information can be collected or transmitted more efficiently between information systems.

c. **Resolution.** It is a combination between the sensor's resolution and its precision depending on the instrumented variable, referring to the capacity it has to detect the variable and estimate the measurement. The values used to discern between the market options are Irresolution, low resolution-low accuracy, low resolution-high accuracy, high resolution-low accuracy, high resolution-high accuracy.

d. **Electronic processing.** Its value increases depending on whether it amplifies the signal if it is done directly, if it has a preprocessing of the variable or if it is capable of collecting the entire sign of the measured variable and taking advantage of that information in a processing unit. The defined values are Null, Amplification, Direct, Preprocessing and Full electronic processing.

e. **Presence.** Its value increases as the sensor can collect the information without being physically on-site. In this way, the sensor can be used in more adverse conditions without sacrificing the measured values. Null, On-site direct, On-site indirect, remote or wireless were the designated values for this characteristic.

ii. Smart

a. **Process control.** It refers to the adaptive capacity of control in terms of the system. It starts from an open-loop operation to adaptive control of the control structure.

b. **Reconfigurability.** It describes the operation that the control has in the manufacturing process and its ability to increase its reconfigurability. Defined values are rigid line, semi-flexible line, single machine multiple processes, single machine modular processes, and reconfigurable production line.

c. **Automation.** As its name implies, it enables specific tasks to be carried out to a certain degree in the manufacturing process. The higher the grade, the more autonomy the System will have. Defined values are not automated, human-automation, partial automation, high automation and fully automated system.

d. **Tasking.** It refers to the control's ability to perform tasks, particularly from obtaining information to carrying them out. The defined values are Null tasking, centralized tasking, decentralized tasking, single network tasking, and multiple network tasking.

e. **Information.** It refers to the control's ability to process data and its interaction with other entities. The defined values are null information, displaying units, monitoring units, processing units, and knowledge generator units.

iii. Sustainable

a. **Goal.** It is linked to the dimension of relevance for the organization, and its interpretation focuses on what the design or redesign of the S^3 manufacturing process will be carried out for. The values it takes are: remain in the market, differentiation, remain competitive, expansion of operations, preserve the environment.

b. **Operations.** It refers to the general operation of the manufacturing process, that is, how much waste is generated, the R3 of the transformation and treatment of the output of the product and scrap production. The levels are

Production of swarf, reduction of scrap, increased efficiency of the transformation process, scrap reinstatement and zero waste.

c. **Energy.** It refers to the treatment and use of the driving force used by the manufacturing process and the origin of the source. The defined levels are Busted energy, Isolated energy, conserved energy, green resources and green and shared energy.
d. **Services.** Similarly, this characteristic evaluates the use of auxiliary services and subsequent treatment to take advantage of this resource throughout the productive system. Defined values are disposed service, service cycle, reused service, service treatment system, and service network.
e. **Emissions.** It is a characteristic of the solutions adopted within the manufacturing process that implies that Sensing has reached a sufficiently high value together with the sustainable objective of the organization since it involves detecting, treating and reducing the emissions generated in the manufacturing process. Its values are greenhouse gas emissions, detection of greenhouse gases, treatment of emissions, reduction of emissions and green processes with a carbon footprint of 0.

The construction of the S^3 Scorecard is done with the value of each of the characteristics of the S^3 solutions implemented in the manufacturing process. Therefore, this graph punctually shows the characteristics that can be improved in existing manufacturing processes to strengthen it.

Figure 4-6 represents the evaluation of a manufacturing process with outstanding solutions in each of the characteristics of the Sensing, Smart and Sustainable attributes. The values that were presented in the list correspond to values from 1 to 5 in ascending order.

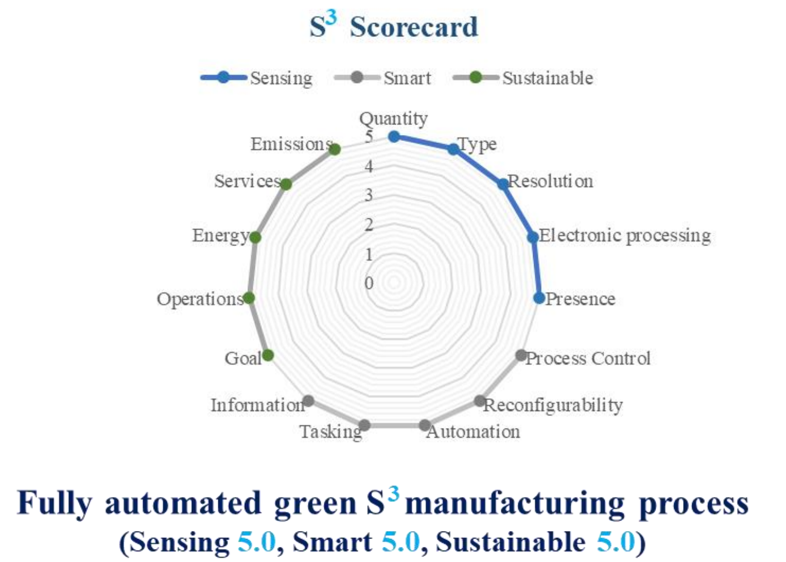

Figure 4-6 Evaluation of S^3 manufacturing process characteristics using the S^3 Scorecard.

As can be seen, the evaluation of the levels is a real number, unlike the taxonomy level. This is due to the evaluation of the characteristics of the S^3 solutions. While the taxonomy has a general objective of automation and sustainability, the assessment can be carried out in detail for each of the generic model's input variables. Therefore, an integer value can be estimated for the design. However, if the solutions are to be implemented, some of them will be lacking at a certain point due to the availability of the market to estimate the variables or to opt for solutions with a higher cost-benefit that do not necessarily increase the solution level.

In industrial solutions, the S^3 Scorecard is of particular relevance because it provides a general overview of the values that can be improved in each solution promptly and reach higher levels (based on the levels of the taxonomy). Likewise, the use of this tool allows the characterization of both the redesign of manufacturing processes and the selection of S^3 solutions in manufacturing processes that seek to strengthen their current levels of automation or sustainability.

The evaluation of the manufacturing processes using the S^3 Scorecard summarizes the system's behaviour, as shown in Figure 4-7. However, the detail of the evaluation can be carried out in specific variables of the manufacturing process that the organization aims. In this way, at least for the Sensing attribute, there would be at least five evaluations for the variables involved in the development and instrumentation.

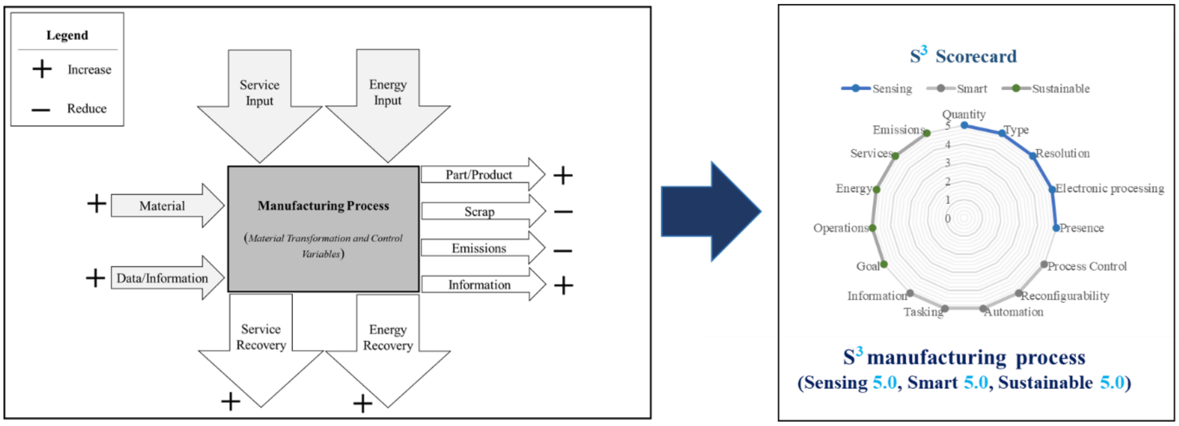

Figure 4-7 Evaluation of S^3 manufacturing processes

The evaluation of the S^3 characteristics of a manufacturing process is still a development in progress. However, it provides an overview of both the initial manufacturing process and the solutions implemented in the manufacturing process. These 15 variables respond consistently when evaluating the S^3 solutions of a manufacturing process.

Based on this tool, the evaluation of the case studies was carried out, and it constitutes the first approximation for redesigns or selection of alternatives. Increasing one of the characteristics of the solutions implies allocating resources and a prior evaluation that can improve the operation of the manufacturing process.

4.3 S^3 Process Development Reference Framework

As mentioned above, three entities make up a manufacturing firm and allow one to differentiate from another. i) Products, ii) processes and iii) manufacturing system. How these entities are carried out is what characterizes the firm and forms an essential part of the business model since the organizational objectives are achieved jointly from the integration of the different stakeholders. The S^3 Process Development RF seeks to incorporate solutions to bring the second entity closer to the paradigms established by I4.0. That is, it aims to be an enabler that helps this process from its understanding to its implementation in a manufacturing firm. The attributes seek to adopt technologies or tools and direct organizational objectives with comprehensive automation solutions that narrow the existing gap and differentiate one organization from another based on how transformation activities are carried out.

The S^3 Process integrates previous knowledge based on traditional manufacturing, the new streams of manufacturing processes, the solutions available in the market and the methodology that allows developing entities in a manufacturing firm. For this reason, the work has been analyzed and justified based on the shortcomings in the literature as a reference model that serves as a guide to define manufacturing processes, the IPPMD RF has been described as the base methodology for the development of entities, it has been used the conception of a generic model for a transformation process, and the taxonomy of the solutions in three different attributes has been described. The S^3 Process Development RF seeks to integrate existing knowledge into a guide that allows designers to incorporate solutions that would enable automation to obtain sustainable processes in the long term and with this, generate gradual growth in the organization, in turn in the region and in turn in the nations where it is established. This approach seeks that any organization can select RF to bring them closer to the paradigms of I4.0 in the industrial context. Thus, it is an enabler of KDMP and IMSy and promotes the growth of nations based on knowledge and objectives aligned with the SDGs from the manufacturing processes conception.

For the creation of the S^3 Process Development RF, it is necessary to remember the IPPMD. Figure 4-8 shows a summary with applications concerning the development of a product, its manufacturing process and finally, its manufacturing system.

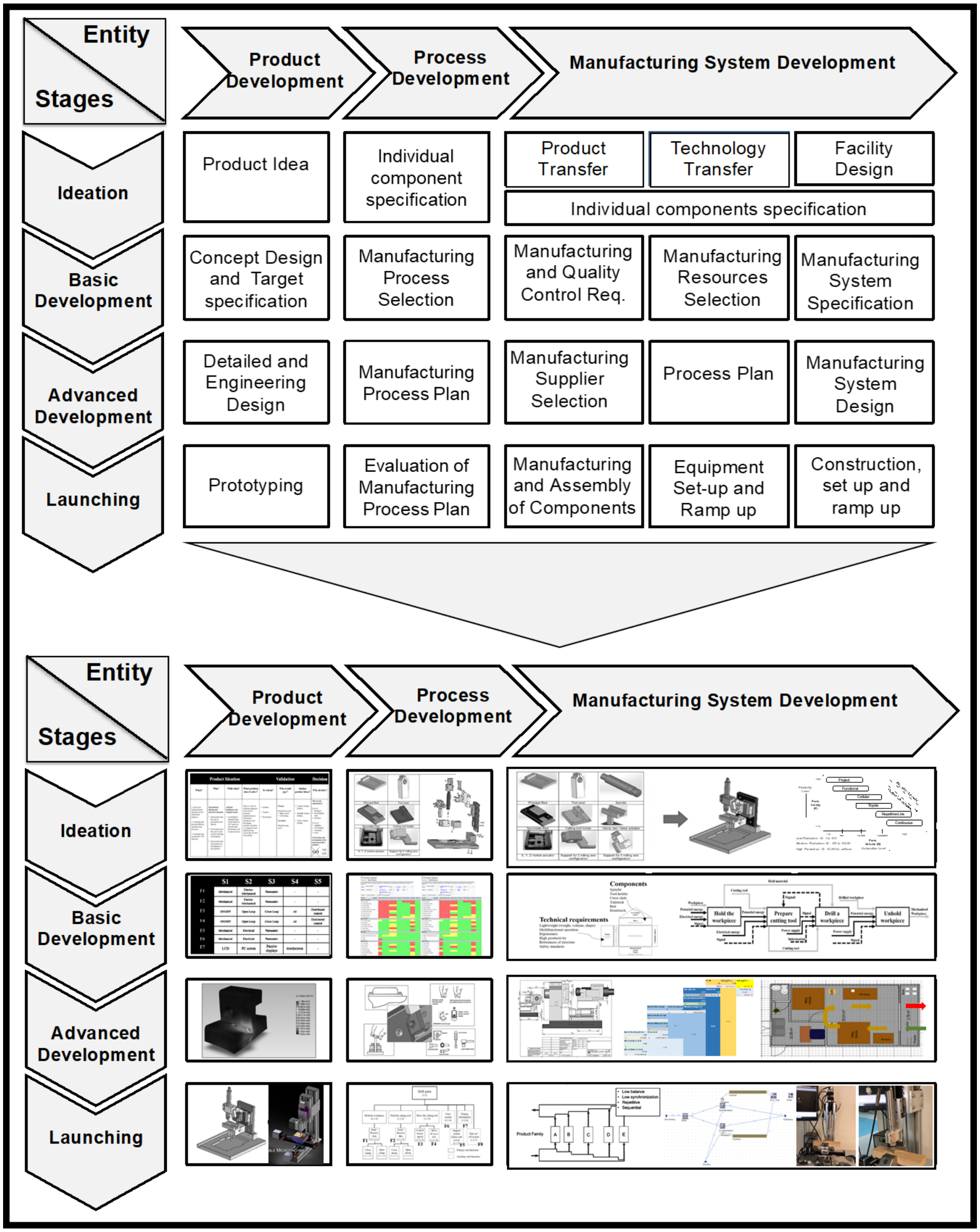

Figure 4-8 IPPMD – Stages for the development of three entities.

As can be seen, the IPPMD RF, for its simplicity, serves as an independent methodology that can guide designers through the manufacturing entity development process. However, this is based on the conception of partial models depending on the point of view with which the activities are developed in a manufacturing firm. In this way, a partial model for developing design activities can consider different axes in an entity and thereby strengthen the methodology during its creation.

Partial design models allow considering viewpoints that are relevant to entity development. Whether in computational, security, engineering, business or use issues, most of them contemplate what is established in the Enterprise Resource Planning (ERP) since these allow control of what happens in the organization (Peña & Villalobos, 2010). An ERP integrates information systems such as operations, marketing, finance in a set of business applications throughout the company. It enables optimized business data processing and vertical and horizontal integration of the organization. Therefore, ERP systems provide an attractive solution to managers who struggle with incompatible information systems and inconsistent operations policies. For a manufacturing firm in the context of I4.0, the one that best provides monitoring of the organization's resources corresponds, on the one hand, to the engineering point of view, which in turn analyzes the functions, information, organization and resources that should be allocated to the entity to promote its development. On the other hand, to develop entities in a manufacturing firm, it is necessary to follow a series of engineering activities that allow analyzing, synthesizing and evaluating the solutions available in the market to implement them (Aurum & Wohlin, 2003). These activities use particular tools depending on the industrial sector, catalogues, databases, norms, best practices, and technologies. Above all, they help document the process and establish tollgates to strengthen development.

Therefore, when combining the intersection of four main stages with the process development entity, the partial model map must be followed to assure engineering activities with the information needed to particularise the model. All in all, applying analysis, synthesis and evaluation activities to a partial model becomes an RF for the process entity of the IPPMD. Thus, activities become steps to achieve the four stages of development. The S^3 Process Development RF is presented in Figure 4-9.

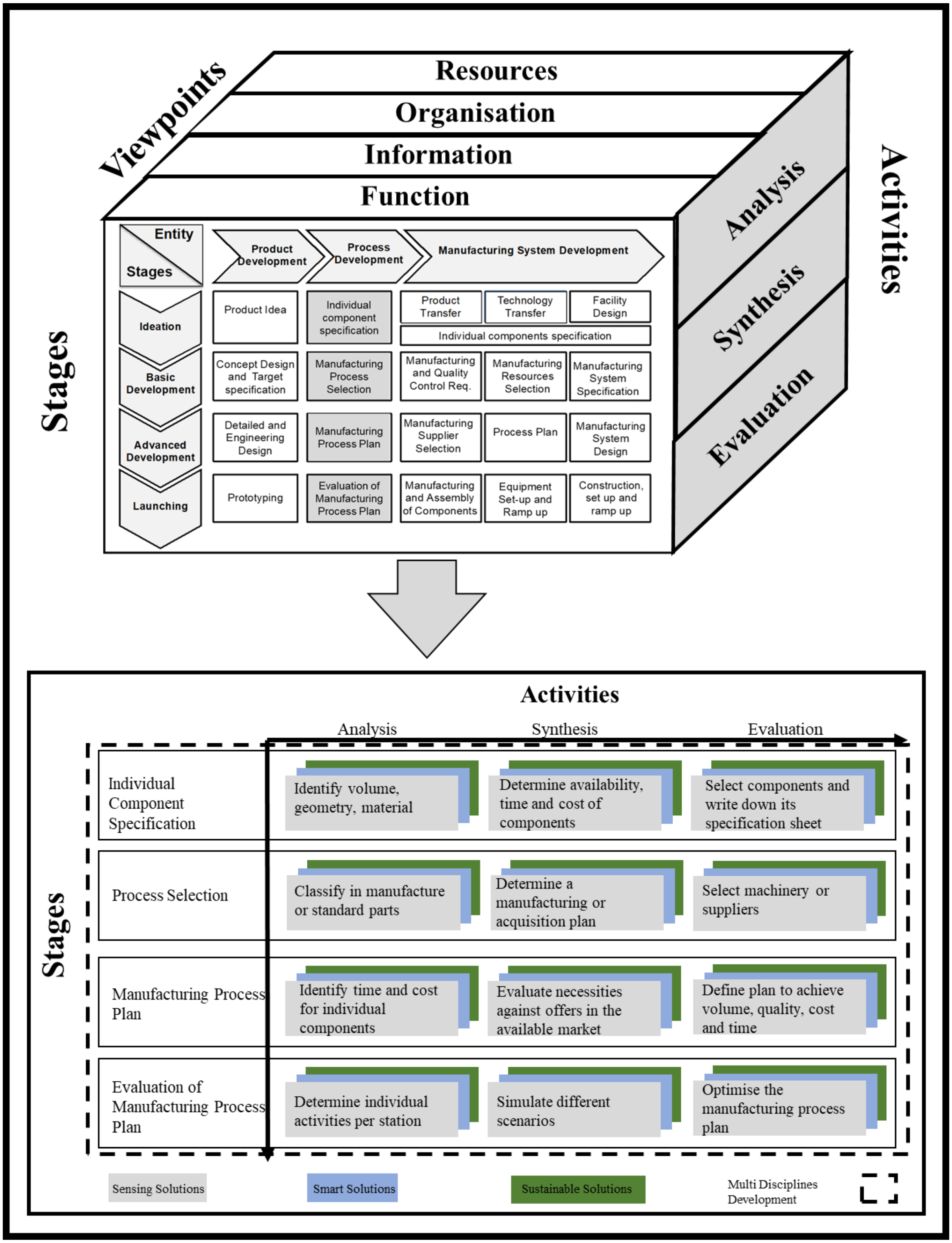

Figure 4-9 S³ Process Development RF.

The S³ Process Development RF presents the activities that must be carried out to complete the stages of the development of a manufacturing process. It comprises analysis, synthesis and evaluation activities in each of the steps, and the dimensions of the S³ solutions are considered. The implementation of these activities for the development of a manufacturing process has decision-making and integrates tollgates for the documentation of the process. This information can be consulted in Figure 4-10.

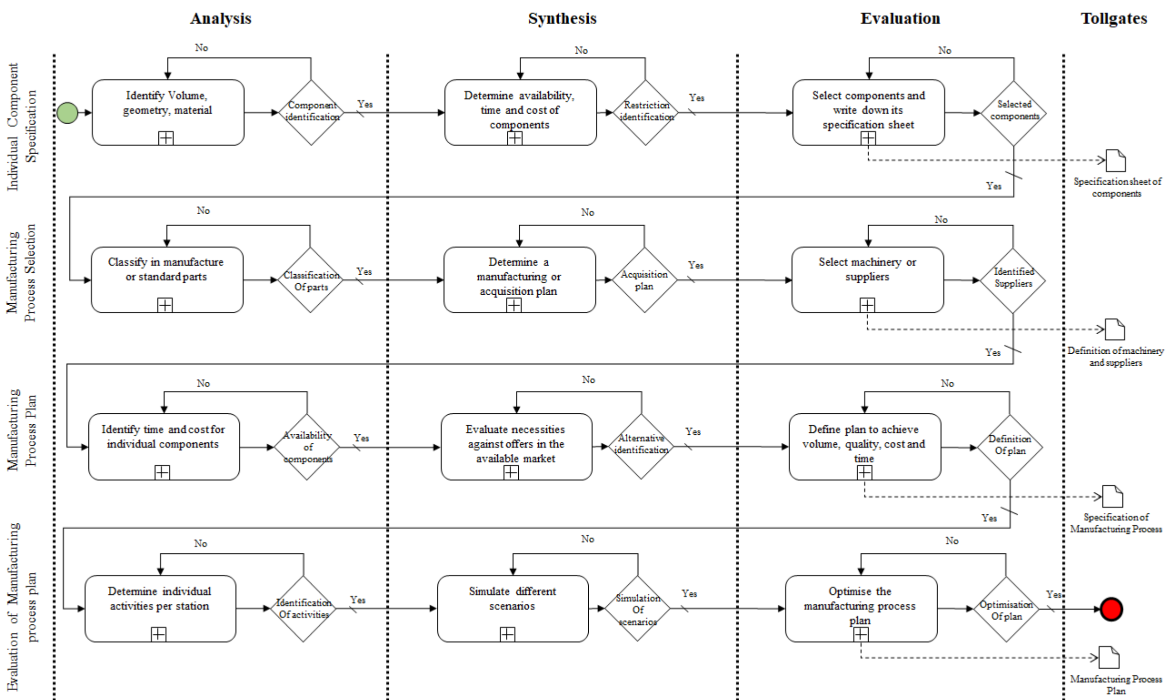

Figure 4-10 Associated activities for S³ Process Development RF.

Thus, using the taxonomy, it is possible to characterize the current manufacturing process and define the objectives to be achieved in each of the attributes. In this way, a lower level is taken as a reference. A strategy to be implemented is to achieve a certain level of automation aligned with the organizational objectives. Subsequently, the S³ Process Development RF is used to break down the activities in the context of the manufacturing process to be developed or updated. In addition, there are a series of regulations that must be taken into account depending on the context in which the transformation process intends to develop or update.

4.4 Toolbox for the manufacturing sector

Table 4-9 summarizes different alternatives to carry out the engineering activities. This contains a Toolbox that needs to be updated depending on the sector in which the design is made. In general, it comprises a set of tools that are useful for new designers.

Table 4-9 Toolbox to support the activities in S^3 Process Development

	Analysis	Synthesis	Evaluation
Individual Component Specification	**Identify Volume, Geometry, Material** Part Cost Estimator Prospector Plastics MMPDS Market research M-Base StahlDat Product Data Sheet Material databases Material archives CES EduPack CES Selector	**Determine availability, time and cost of components** Prospector Plastics Bosch Bolt Depot Ytfasteners Online catalogues Catalogues Parts CES Selector Part Cost Estimator	**Select components and write down its specification sheet** Life Cycle Assessment Cost-Benefit analysis Pugh Chart Function Decomposition Matrix Morphological Matrix Solution Matrix Bill of Materials
Manufacturing Process Selection	**Classify in the manufacture or standard parts** Product Catalogues Functional Decomposition Process Selector	**Determine a manufacturing or acquisition plan** Matrix of creative stimuli Axiomatic Design Concurrent Function Deployment QFD Triz Checklist	**Select machinery or suppliers** HOWs Chart House of Quality Pugh Chart Process Selector PRIMA Matrix Manufacturing Weight Matrix
Manufacturing Process Plan	**Identify time and cost for individual components** Material databases Material archives CES EduPack CES Selector Part Cost Estimator Critical Path Method Program Evaluation and Review Technique	**Evaluate necessities against offers in the available market** Morphological Matrix Graphical Evaluation and Review Technique Gantt QFD Triz Matrix of creative stimuli Axiomatic Design Precedence Diagram Method Project Evaluation and Review Technique Line of Balance Critical Chain Method Dependency Structure Matrix	**Define a plan to achieve volume, quality, cost and time** MPX Critical Path Method Program Evaluation and Review Technique Identify process standards for manufacturing components Value Stream Mapping Critical-Path Mapping

	Determine individual activities per station	Simulate different scenarios	Optimise the manufacturing process plan
Evaluation of Manufacturing Process Plan	Production Attainment Percentage planned vs emergency maintenance work orders Availability Yield Supplier quality incoming Customer fill rate Supply strategies Simulation Time and motion Manufacturing Cycle time Time to make changeovers Throughput Capacity utilisation Overall Equipment Effectiveness Schedule	CGMA Quality strategies Cost reduction Environmental effects Regulatory compliance Organisation strategies Area distribution Layout Discrete Event Simulation What if scenarios Scenario Evaluation Tool Scenario Analysis	FMEA Manufacturing Cycle Time Throughput Capacity utilisation Availability of continuous resources Life Cycle Assessment Evaluation of Discrete Event Simulation Assessment of Value Stream Mapping

The use of the S^3 Process Development RF is not affected by the manufacturing sector. The activities correspond to those mentioned. However, the tools, standards, norms, development time and tollgates may be affected. Therefore, the selection of appropriate tools can condition the development of manufacturing processes in different sectors.

4.5 Methodology for S^3 Process Development

The S^3 Process Development RF comprises the stages of development or updating of a manufacturing process. It relies on the generic model and engineering activities for its development. However, this stage, although critical, corresponds to the last stage of the methodology. This methodology is precisely what the manufacturing process development literature lacks.

The methodology for developing the S^3 Process comprises three fundamental steps. In these stages, the generic model, the taxonomy that describes the system, the analysis, synthesis and evaluation activities are developed, various tools are used to carry them out, and finally, the development with the tollgates of the sequence of activities is documented. The description of the methodology is as follows:

i. **Definition of Manufacturing Process.** In this step, the phenomena that govern the manufacturing process are studied. It is characterized using the generic model. The variables that govern the system or control variables, the information required to carry out the process, the materials and the energy and auxiliary services of the same are identified. In addition, the manufacturing process in question is described of its S^3 characteristics and is linked to the automation and sustainability objectives of the manufacturing firm.

ii. **Sequence of activities.** For this, the engineering activities that best describe the manufacturing process are defined. Since it is an iterative process, the actions should be repeated to refine the information. In this stage, the Toolbox is used, and the progress in the activities promotes the development of subsequent phases.

iii. **Instantiation.** This process corresponds to the definition of the particular model, taking into account the specific norms, standards and restrictions for the industrial sector in which the manufacturing process is developed or updated. The previously defined activities are implemented, and the documentation is collected in each of the stages that comprise the manufacturing process entity.

iv. **Evaluation.** In this stage, the initial design of the manufacturing process is compared with the implemented one. The S^3 Scorecard is used to evaluate the attribute values of S^3 solutions. In addition, the development team must make recommendations to improve the manufacturing process either in terms of automation or sustainable objectives for the organization.

As detailed in the taxonomy, this methodology has been used at least during the development of the following three applications.

i. **Design manufacturing processes with S^3 solutions based on a product.** This type of development is exemplified in the 3D Food Printer case study.

ii. **Characterise existing manufacturing processes and improve their S^3 attributes.** The case study of the redesign of the Micromachine's lathe module has been detailed for this application.

iii. **Selection of S^3 solutions in manufacturing processes.** An industrial case has been developed that matches this type of application. The third case study details the selection of S^3 Solutions in the Leak Test manufacturing process.

The methodology for developing S^3 processes is presented in Figure 4-11, and based on this, the case studies of chapter 5 are shown.

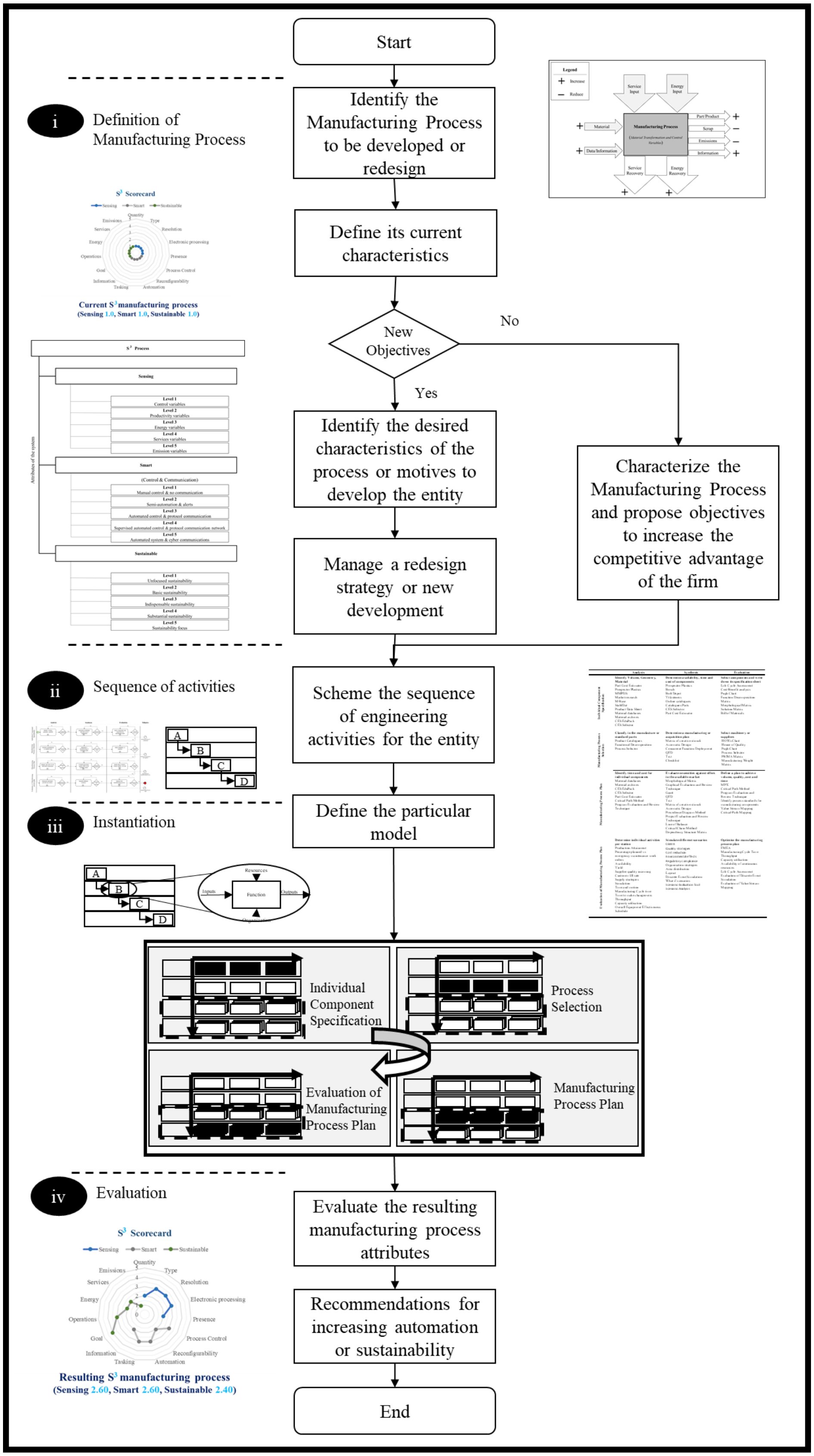

Figure 4-11 Proposed methodology for the development of the S³ Process.

Chapter 5 Case Studies

This chapter explores three different case studies related to the industrial environment. Each of them is based on the previously defined applications on the application of the thesis work contributions.

The first one refers to ***design manufacturing processes with S^3 solutions based on a product***. It explores the design of a manufacturing process to help health problems in infants and elderly people. Its implementation was concluded as a mountable module in a reconfigurable CNC machine. The project was called 3D Food Printer. It collaborated with the Universidad de Los Andes for its development.

In the second, there is presented a ***characterisation of existing manufacturing processes to improve their S^3 attributes***. a product developed at the Monterrey technology company was taken as a technological base to equip it with S^3 solutions. The reconfigurable Micromachine Tool was redesigned from version 1 to version 3.

Finally, in the third case, the ***selection of S^3 solutions in manufacturing processes*** to redesign of a manufacturing process of a manufacturing supplier of the automotive industry is explored. The project analysed the current state of the leak testing process carried out in the production lines, and the aim was to increase the levels of automation of the process.

During each of the case studies, an analysis of the characteristics of the manufacturing process was carried out. It was broken down into its essential solutions, the control variables, material, information, energy and required services. Subsequently, different engineering activities were carried out to increase the level of its characteristics according to the reasons for the project. Finally, proposals were made to increase these levels and analyse the initial and final state under the proposals.

It should be noted that the descriptions of the generic model, the S^3 Process Development RF, the taxonomy, the toolbox and the instantiation of each of the study cases were used. A recommendation to follow the proposed methodology is to characterize the current level of the manufacturing process, based on the objectives of the project or the manufacturing firm, define the desired levels of automation and carry out the four stages of development of the entity of manufacturing process.

The following is a preamble to each case study, the development and the results obtained following the proposed methodology.

5.1 Design of S^3 manufacturing process of the 3D Food Printer

In the first case study, food production is explored. The project aimed to offer a practical solution to nutritional problems in the most remote rural areas. The project was developed to attack Zero Hunger's SDG. It was a joint work between universities in Colombia and Mexico. Universidad de Los Andes and Tecnológico de Monterrey respectively. Objectives of this research contribute to state of the art in manufacturing design and nutrition fields. The former is treated in this dissertation. However, this project aims at providing a solution to existing problems regarding nutrition. The primary motivation for this project is related to the current nutritional deficit indexes both in Colombia and in Mexico. The situation is worrying due to the high level of malnutrition that exists in rural areas. However, there is an overproduction of fruits and vegetables, which are wasted annually.

There are problems associated with malnutrition, especially in infants and the elderly. The root of these problems lies in food prices, the vulnerable population's low income, and the scarce information related to eating habits in general. The complexity of this project has different aspects, the issue of food security, the production of nutritious foods on a large scale, the use of the overproduction of resources such as vegetables and fruits, the collection of surpluses and the system that allows the production of nutritious foods. The selection of the problems given the profile of the collaborating researchers was based on i) the design of the production system, where ii) an edible formula based on fruits present in Colombia and Mexico was processed. This selection delimited the case study and allowed two groups to work on it simultaneously. The edible formula that was developed was based on mango and xanthan gum to be enriched with vitamins or nutrients according to the needs of the target population. Definition of the problem, the first approach of this research, and the product design development entity methodology are exposed (Cortés, Rodríguez, et al., 2018b).

However, despite developing the formula as a food product, the problem lay in establishing a manufacturing process capable of processing it. Since the manufacturing currents are based on the flexibility of production lines, modularity when carrying out the operations and customization, food printing was selected as a portable alternative that solves the problem of transportation and production of nutritional bars in rural zones. The platform on which this project was developed was the updated version of the second case study. For this development, the methodology proposed in this work was followed. The set between machine and module capable of carrying out the transformation process of food bars was named 3D Food Printer machine.

The main target of this case study was defined as the manufacturing process that involves this transformation. Decomposing the main activities needed, identifying the available components in the market and adapting them into a manufacturing system to design an S^3 Process. During the development of this project, two main approaches were treated: i) nutrition and ii) transformation involved. On the other hand, the transformation was addressed following the methodology previously exposed in this work to design the 3D Food Printer.

The manufacturing process has been characterised, and its critical features have been selected to implement the solutions. The desired S^3 levels have been established using the Taxonomy exposed, and the S^3 Process Development RF reference model has been followed during the design process. The results have been evaluated using the S^3 Scorecard. The following is a summary of the stages, activities and findings during this process.

The case study was developed in conjunction with nutrition personnel, biotechnologists, structural mechanics, mechatronics and industrialists; therefore the previous requirements to solve the case study are detailed in table 5-1.

Table 5-1 Knowledge requirements to develop the 3D Food Printer

Development	Identified areas	Participant's profile	Relevant knowledge applied
Food extrusion system	Mechanics Computing and software Control	Mechatronics engineer Industrial chemical engineer	Analysis of the food extrusion process Nozzle displacement analysis Plunger displacement velocity analysis Effect of displacement pressure on the amount of material deposited Selection of safe material for ailments Adaptation of standard components to the food extrusion system Selection of materials for the work bed Development of hot and cold bed for the extrusion of the edible formula
Edible nutritious formula	Bio engineering Structural composition Ailment engineering	Industrial chemical engineer	Viscosity and structure analysis of edible material Filament size Transport system for vitamins Support material and food base Consistency analysis in working conditions Thermal analysis of food material
Physical support structure	Mechanical	Mechatronics engineer Industrial chemical engineer	Support structure design Adaptation of the displacement of the work bed in the X and Y axes Transformation of the Z and A axes for the vertical movement of the filament and extrusion system Edible material loading system Adaptation of 3D Printer operation to 3D Food Printer system

5.1.1 Definition of Manufacturing Process

The manufacturing process for the production of solid-based food, at an industrial level, corresponds to the preparation of formula in containers, deposition of it in portions and post-process to add flavourings, minerals or a pre-cooking process as shown in Figure 5-1. The food printing module replicates this industrial behaviour on a smaller scale but allows the deposited formula and post-processing customisation. The design of the process contemplates adding the vitamins required for personalized intake of those who need it most.

The idea behind the processing machine works as follows. The preparation of the formula is carried out externally in innocuous containers. Then, the food printing module focuses on the portions delivered by the container in a personalized way. The module is equipped with cold or hotbeds to counteract the delivered viscosity of the formula and allow the product to adhere in the desired manner. After this process, the products go to a laboratory to be added with vitamins and packaged.

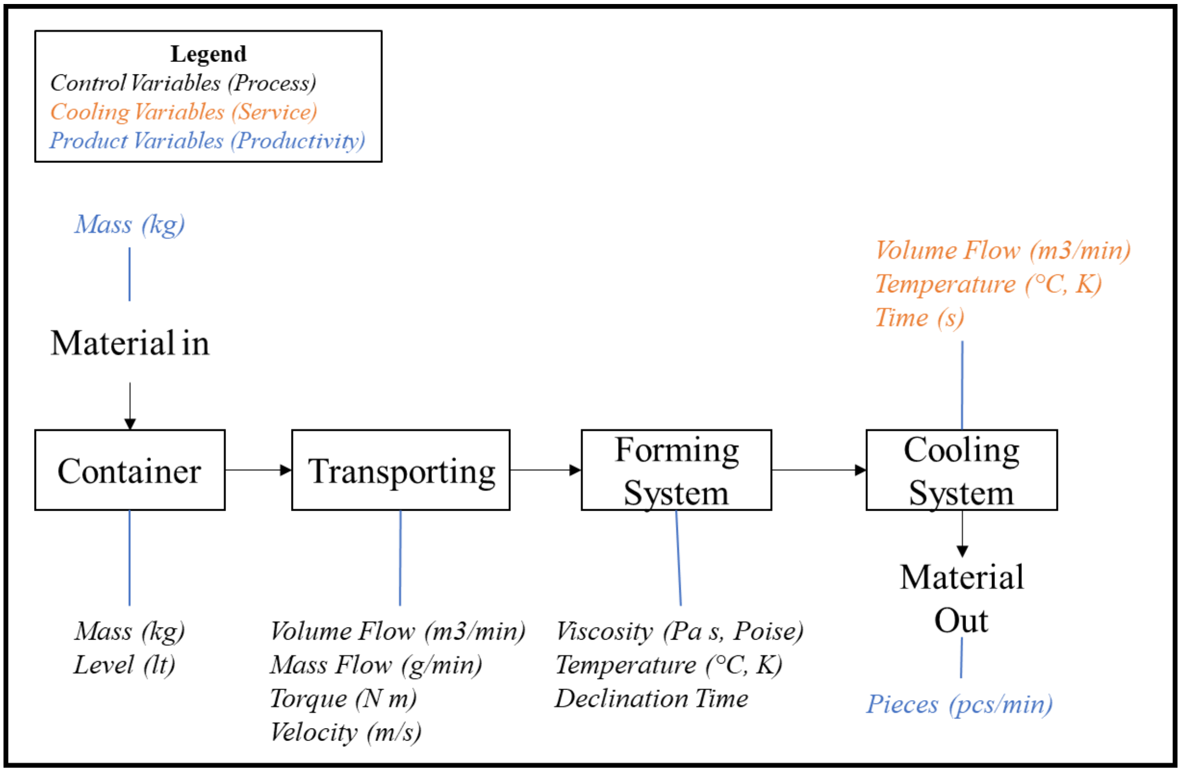

Figure 5-1 General process for solid-based food.

Because the edible formula has been developed to use mango pulp and xanthan gum as an emulsifier, the raw material can be stored for a long time and transported to the place of origin. However, it must be mounted on a device capable of printing it on the go at the time of preparation. The product requirements for the development of the manufacturing process are listed below:

1. ***Nutritional characteristics***. The edible formula must be optimal for children and elderly people consumption.

2. ***Taste characteristic***. The edible formula must be tasty for potential customers. The experiment design presented in this article resembles this characteristic among the

potential customers. However, at the same time, mechanical attributes of the formula are tested to accomplish the declination time of the final product.

3. ***Mechanical characteristic***. All the automated solutions must be standard and capable of processing the edible formula. The mechanical base is comprised of 3D printer components but adapted to address the viscosity needed.

4. ***Formula***. The edible recipe could be reproduced following a preparation manual that includes pre-fabrication, a series of steps and post-fabrication treatment.

5. ***Manufacturing system***. The manufacturing process must be able to produce customizable products using the edible formula. Viscose formula is expected, mechanical components must be capable of shaping a final product.

6. ***Hardware specification***. Every part of the manufacturing system must be specified according to standard components.

7. ***Software specification***. The manufacturing system should process nutritious edible dough into desired forms using Computer-Aided Design (CAD).

8. ***Modularity***. The manufacturing process must be designed to be adapted into developed technology. Thus, an innocuous design must be adapted as a whole, considering the main aspects of the process.

So it was necessary to include certain features that allow the automation of the manufacturing process while pursuing its efficiency. Therefore, the manufacturing process design was selected using the technological base of chocolate, sugar or pasta-based food printers. That allowed the customization of i) the nutrients required by the target population during material loading and ii) the model of choice, whether in the form of a bar or proprietary design. In this way, the machine could be used for personal use or with non-profit organizations seeking to positively impact society by reducing hunger in rural areas.

Once the challenges of production, use and installation have been identified and a general outline of how solid base foods are produced on a large scale, the generic model, is to be developed as specified in Figure 5-2. For this selection of machine, various tests of the extrusion mode were developed, mechanisms were acquired to transport food and tests were carried out so that its execution worked with a plunger to minimize material waste, and its cleaning could be carried out between edible loading formula in the machine.

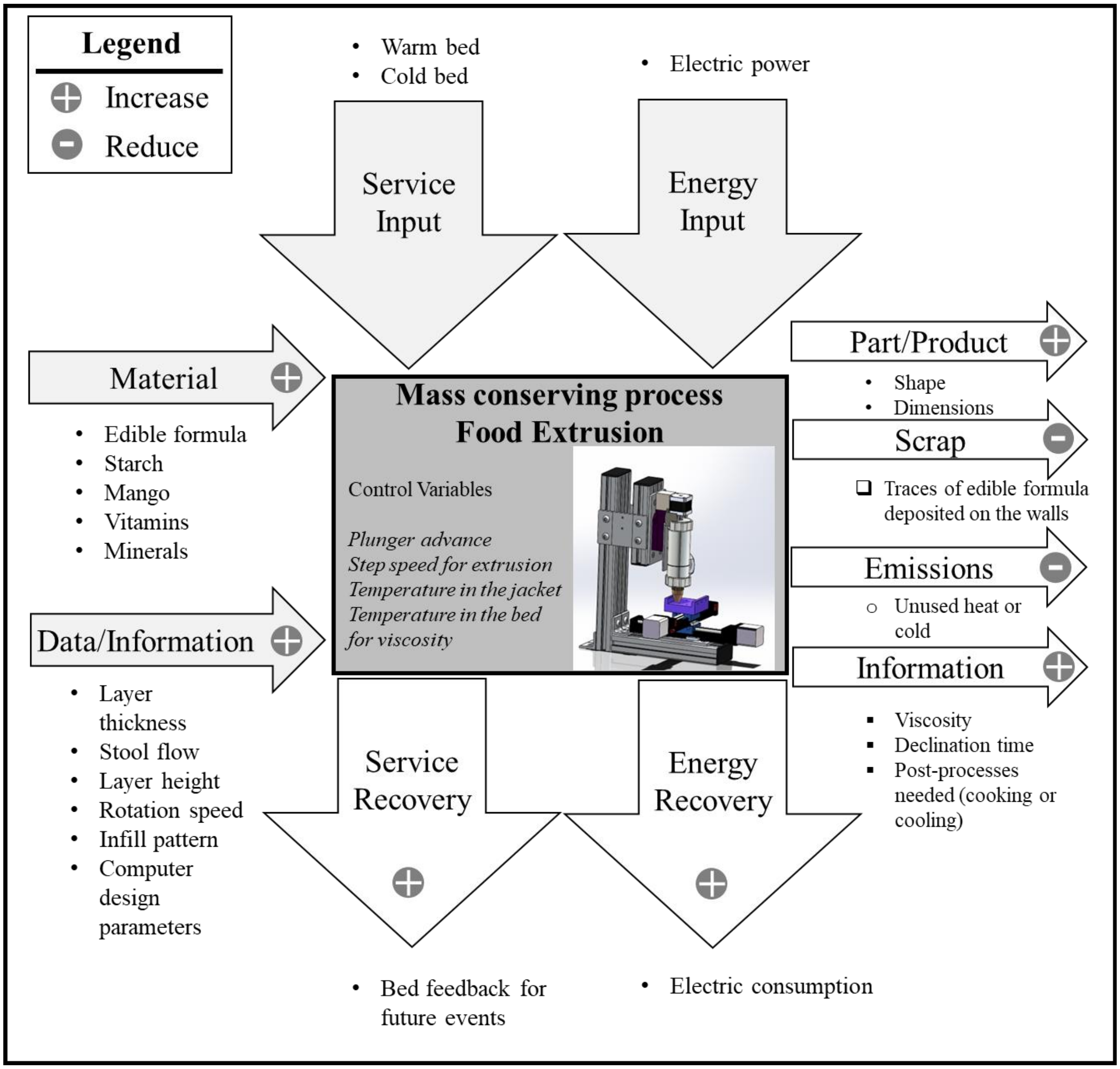

Figure 5-2 Generic model for the 3D Food Printer.

As shown in the figure, the manufacturing process is one of mass preservation, and the transformation carried out is the extrusion of food through a nozzle. This allows working with a filament similar to that of 3D printers. The material used is the edible formula that uses mango and a means of transport in which vitamins and minerals can be added during preparation. To carry out the process, it is necessary to define the shape to give the product obtained. This depends on the nozzle and conditions, the capacity of the material, the filling pattern, and the rotation speed of the Z-axis and the post-design processing. The auxiliary bed service is used, which can be cold or hot depending on the viscosity of the transport fluid in the formula; starch and xanthan gum were used, each with its restrictions. However, this transport is subject to change and therefore, the machine considers both beds in its design. It uses an electrical current to power three stepper motors, one for each axis and the bed. The movement is carried out in the X and Y axes, and the Z-axis corresponds to material extrusion.

The finished or semi-finished product is the output of the manufacturing process; depending on the type of formula, a cooking or cooling process can be carried out, which goes hand in hand with the viscosity and temperature of the place where the product is carried out. In addition, to complete the output information, the manufacturing process has the decline time of the material. Some deformations occur over time in the techniques that work with filament. The emissions of the process correspond to the energy wasted during its cycle, while the scrap that is had is only the residues of the walls, therefore the importance of the size of the plunger, to reduce it. Regarding the recovery of energy and services, the design only contemplates its measurement of the services. It is possible to use this information to maintain the bed's temperature and use it in future loads of material.

Once the manufacturing process was identified, and its inputs and outputs were defined, the taxonomy was used to determine the variables to be monitored, as well as the level of automation to be achieved and the sustainable objectives of the machine. The product requirements were compared with the definitions of the taxonomy levels to match the theoretical solutions with the needs of the 3D Food Printer. Thus, the S^3 levels of the solutions were 2,2,2 in each of the attributes, respectively.

These levels allow characterizing the manufacturing process as an S^3 Process. The implementation of the characteristics to achieve the levels is what will determine the success and objectives pursued by the designed manufacturing process. The description of each of the features to be implemented is shown in Table 5-2.

Table 5-2 S^3 solutions in the 3D Food Printer

Characteristic	Solution	Description
Sensing	Monitoring	• Processing time is measured and control before printing the product. • Productivity is monitored aided by presence sensors in the deposition bed • Scrap is observed at the end of the processing cycle. • Energy consumed is registered. • Services are controlled using Peltier cell or heat cell to compensate for the viscosity of the edible formula • Emissions are measured in terms of the services. All the energy is measured but not controlled nor feedback to the system.
Smart	Control	• The module is designed to function in an open-loop control • Axis A feeds back due to the current position of the piston • Axis A controls the container provided with a quantity of edible formula. It alerts when there is not enough printing material. • The module could be operated through ethernet protocols using a PC.
Sustainability	Design	***Economic:*** • Suppliers check components, and there is a quality control inspection when they arrive at facilities • Standard features are used for the module • A plate must be adapted to the module. However, it is helpful for different modules to decrease costs ***Environmental:*** • All components of the module are recyclable • Eco-friendly elements are searched for the composition of the module ***Social:*** • Direct contact materials with edible formula are innocuous • Standard height and measures are considered for ergonomics during production time • The software environment is easy to use for a different types of operators
	Manufacturing	***Economic:*** • The edible formula is prepared in situ, but a receipt is provided to decrease swarf • Assembly operations to mount the module takes no longer than 15 minutes. • The maintenance of the module is reduced due to standard components • The working area allows multiple edible designs ***Environmental:*** • The manufacturing process generates low emissions • Energy consumption is minimal to produce the ailments ***Social:*** • Ergonomics have been tested for the module and its operation
	End-of-life	***Economic:*** • There is a deposition plan for the module at the end of its life ***Environmental:*** • Standard components are easily interchangeable • The body structure of the module is recyclable ***Social:*** • It does not apply

The table shows the characteristic that corresponds to each of the Sensing, Smart and Sustainable attributes, the type of solution used to implement this characteristic in the machine and the description of what was designed. Sustainable goals tie in with the device's design, both for personal use and for non-profit organizations. The objective is that this manufacturing process has an economic impact for those who produce it, an environmental impact regarding the materials used and a social impact on the people involved.

With the complete generic model and the S^3 solutions proposed, the methodology continued defining the sequence of activities for the entity's realization of the manufacturing process in a structured way, as shown in the next section.

5.1.2 Sequence of activities of the 3D Food Printer Module

Once the levels of the S^3 solutions were defined, the Toolbox from Chapter 4 was used to describe the sequence of activities during the development of the 3D Food Printer. Table 5-3 shows the stage of development of the entity of the manufacturing process on the left side; on the centre, there are shown the engineering activities for the development of the process, and at the right side, the tollgates are presented for the documentation of the machine

Table 5-3 Toolbox for the 3D Food Printer

	Analysis	Synthesis	Evaluation	Tollgates
Individual Component Specification	**Identify Volume, Geometry, Material** Part Cost Estimator Market research Product Data Sheet Material databases	**Determine availability, time and cost of components** Online catalogues Catalogues Parts	**Select components and write down its specification sheet** Function Decomposition Matrix Morphological Matrix Solution Matrix Bill of Materials	**Specification sheet of materials for the 3D Food Printer.**
Manufacturing Process Selection	**Classify in the manufacture or standard parts** Functional Decomposition Standard components Electronic kits (Smart suppliers) Sensing solution suppliers	**Determine a manufacturing or acquisition plan** Checklist Assemblies/ subassemblies of the manufacturing process	**Select machinery or suppliers** Process Selector PRIMA Matrix	**Definition of machinery needed, tools, supports and suppliers.**
Manufacturing Process Plan	**Identify time and cost for individual components** Material databases CES EduPack Part Cost Estimator KWh analysis for Sensing and Smart solutions	**Evaluate necessities against offers in the available market** Morphological Matrix Gantt Precedence Diagram Method	**Define a plan to achieve volume, quality, cost and time** Critical Path Method Identification of norms and standards Value Stream Mapping Cost analysis	**Specification of the manufacturing process for the 3D Food Printer**

Evaluation of Manufacturing Process Plan	**Determine individual activities per station** Supply strategies Time and motion Capacity utilisation Overall Equipment Effectiveness	**Simulate different scenarios** Area distribution Layout Discrete Event Simulation	**Optimise the manufacturing process plan** Life Cycle Assessment Evaluation of Discrete Event Simulation Assessment of Value Stream Mapping Deadtime reduction	**Manufacturing process plan evaluation**

The sequence of activities allows the gradual development of the manufacturing process. In each activity, tools or techniques have been included to analyse different aspects of the manufacturing process during its construction. Finally, the tollgates help organize the results obtained from the methods to document the design. This sequence of activities was defined for an S^3 Process of the 3D Food Printer design. A group of developers can begin to carry out the activities individually, and their integration would result in the elaboration of the machine.

5.1.3 Instantiation of the 3D Food Printer

The instantiation corresponds to the development of the activities in the engineering environment carrying out the analysis, synthesis and evaluation activities. During this development, the best alternatives, selection of materials and implemented solutions are analysed. Since it is part of an iterative process, the previously defined sequence helps avoid excessive iterations in the process and structures the development of the stages. The sequence of activities was carried out following the four design stages and implementing the engineering activities. Table 5-4 shows the tools used and the breakdown of the work done by step.

Table 5-4 Instantiation for the development of the 3D Food Printer

Stage	Engineering Activities	Tools/Documentation
Individual Component Specification	*Identify volume, geometry, material* • Determine the total volume that will be produced by the module and determine the capacity of the container. • Identify the commercial components available that fit the innocuous aspects and mechanical requirements • Decompose the module by parts and its functions. • Define the required volume, geometry (complexity of the shape) and material for individual components of the module • Determine the characteristics of the components: shape, roughness, tolerance, mass. • Identify the sustainable impact of the components according to its manufacturing process • Search for sensors solutions for the manufacturing process, productivity, energy, services and emissions	• Material databases • Product data sheet • Electronic suppliers
	Determine availability, time and cost of components • Identify suppliers, similar components and viability to obtain components regarding the demand needed. • Determine solutions that would not affect the integrity of the final product • Determine where the sensors and electronics for its functioning is going to be located	• Online suppliers • Catalogue parts • Databases • Electronic solutions

	Select Components and write down its specification sheet • Identify different parts that could be used as a contingency plan according to their functions • Select components with the value-added characteristics needed • Select feasible sensing solutions for the five features needed. • Identify suppliers to cover the demand and generate a catalogue. • Write down the physical characteristics of the components as they are going to be used as restrictions when selecting the machinery	• Morphological matrix • Function decomposition • Solution matrix • Bill of Materials
Process Selection	*Classify in the manufacture or standard parts* • Classify the components in two groups: i) manufacture components (not standards components and an internal or external manufacturing system must produce them) and ii) standard components. Identifying the sustainable impact of the components • Differentiate the sensors by presence to include in the diagrams • Search for smart solutions to cover the maximum number of sensors if possible • Establish the array of Sensing and Smart solutions	• Functional decomposition • Standard parts catalogues • Electronic kits • Sensing solutions
	Determine a manufacturing or acquisition plan • Standard components are acquired. Determine an acquisition plan with suppliers to deliver the components strategically, reducing waiting time and assuring a continuous flow of material • Determine if there is going to be needed additional processes for standard components as finishing processes. Milling, Drilling, Cutting, Laser Engraving, among others • Manufacture pieces must be produced. There are two options during manufacturing components. The first is to establish a sub-process where non-standard components are produced; they are unique and adds value to products. The second is to establish a relationship with external manufacturers and determine the number of components to produce and deliver to satisfy the demand	• Checklist • Assemblies/Subassemblies
	Select machinery or suppliers. • Select suppliers for those standard components. Select machinery for manufacturing processes. Select stations or machinery for finishing processes • Select the distribution of the Sensing and Smart solutions	• PRIMA Matrix • Process Selector • Smart systems
Manufacturing Process Plan	*Identify time and cost for individual components* • Determine material flow for assuring a continuous processing cycle • Determine packing and logistics for raw and finished products • Determine the cost of machinery, tools, commodities and additional services needed to keep continuous operations • Determine the number of sensors and processing units needed • Determine the impact of the solutions adopted	• CES EduPack • Part-cost Estimator • Material Databases • LCA • KWh from sensors and smart system
	Evaluate necessities against offers in the available market • Verify the dimensions, finishing and effectiveness of components. • Identify the sustainable impact of the components • Compare the quality of the supplies against what would be offered • Compare lifetime and efficiency among the Sensing and Smart solutions	• Gantt • Morphological matrix • Precedence Diagram Method
	Define a plan to achieve volume, quality, cost and time • Define production planning considering the volume of the products to be produced in the period defined • Determine the delivery periods and productivity calendar • Determine the quality parameters, processing time, number of operators, number of machines, cost and sale price. • Determine the best set of sensing solutions • Determine the best set of smart processing units • Determine the best distribution in the manufacturing process and its array	• Critical path method • Value Stream Mapping • Identification of Standards • Life cycle Assessment • Cost analysis.
Evaluation of Manufacturing Process	*Determine individual activities per station* • Determine data and reports needed • Schedule shifts and individual tasks • Determine the number of operators and all supplies needed per station • Determine buffers and cycle times • Schedule maintenance of machinery • Determine the impact of the solutions adopted	• Capacity utilisation • Supply strategies • Time and motion
	Simulate different scenarios • Use scenario-based techniques to represent different scenarios • Use Discrete Event Simulation to simulate operations of the manufacturing process • Simulate real distribution of the machinery • Simulate real operation cycles with time • Simulate failures of the sensing and smart solutions adopted • Prepare a contingency plan.	• Discrete Event Simulation • Digital representation • The layout of the manufacturing process
	Optimise the manufacturing process plan • Find optimal routes, number of workers, shifts • Find optimal cost • Fin optimal machinery • Find the best array of sensors and smart solutions to assure continuity in operations. • Be conscious of the impact that the S^3 solutions generate.	• Life Cycle Assessment • Evaluation of Discrete Event Simulations • Evaluation of Value Stream Mapping

The development of this machine has been carried out in the four stages of the S^3 Process Development RF. The activities that have been carried out correspond to the instantiation table. Figure 5-3 shows the activities carried out in each, and a summary is presented. In this way, the techniques have been carried out to show progressive advances in the process. From the selection of materials to the evaluation of the manufacturing process, the stages consider the optimization of resources, in order to meet the sustainable objectives of the project.

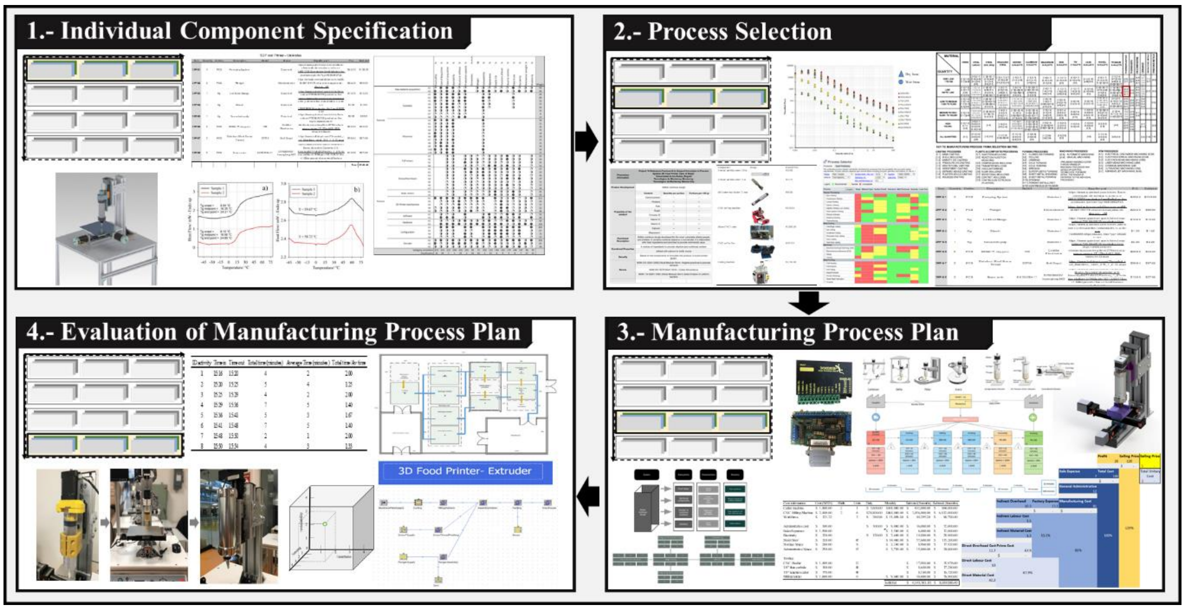

Figure 5-3 Summary of the 3D Food Printer S^3 Process Development.

The 3D Food Printer is an option in the mass preservation manufacturing process. Sensing and Smart solutions have been adopted that allow automating parts of the transformation process and meeting sustainable objectives aligned with the primary goal of the process. The activities that have been carried out allowed the realization and documentation of the machine that fulfils the function of extruding customizable food, both in shape and nutrients. The results and evaluation of the S^3 characteristics will be shown in Chapter 6.

5.2 Redesign of the S^3 manufacturing process of the Reconfigurable Micro-Machine Tool

Existing Computer Numerical Control (CNC) machines are intended for high-speed, high-precision and large production volumes, requiring specialized labour to operate and repair them. In addition, the cost of spare parts and acquisition is often high for most users interested in this technology (Plaza & Zebala, 2019). Any failure in the machine would affect the precision and efficiency of machining, leading to a possible reduction in the quality of the manufactured components. (Wan, Gao, Li, Tong, & He, 2015) Besides, the maintenance costs of CNC machine tools represent between 20% and 30% of the total life cycle costs from ranges between USD 13,000 to 78,000 annually (Yao & Zhou, 2014)(Adu-Amankwa, Attia, Janardhanan, & Patel, 2019).

These types of machines are developed to perform specific machining functions. Therefore if a part requires different manufacturing processes, this would mean having several dedicated devices, which may be economically unfeasible on a small scale (Hawksworth & Cookson, 2006; INEGI, 2018). When talking about small-scale projects, portability is usually an essential element since it is often necessary to constantly migrate it to different work areas (Lotti, Villani, Battilani, & Fantuzzi, 2019). The strengths of MSMEs have set the trend in the context of I4.0, as they align with the marketplace movement and allow organizations to introduce new products in an agile way, flexibility in production lines and the ability to survive harsh environments full of competition (Cronin et al., 2019).

Currently, the manufacturing learning platforms in schools are industrial production machine tools. Its operation and maintenance are expensive (Rodríguez, Estrada, Hernández González, & Ochoa, 2008). This means that the learning units limit students' knowledge, who have little interaction with industrial tools (Rolstadås & Moseng, 2002). Manufacturing trends indicate that students from various areas of engineering must have knowledge and practice in the area of computerized machining. However, because few schools can afford to have machines to operate and maintain the appliances, they turn to software simulation or training on a single device with limited hardware (Browder, Aldrich, & Bradley, 2019).

Students' knowledge and skills are often diminished by not practising correctly (Orjuela, Arroyo Osorio, & Rodriguez-Baracaldo, 2013). To all this, it should also be considered that G. Bengu and W. Swart mentioned that education in manufacturing was not consistent with recent advances in the industry and that to improve it, it was necessary to change not only the teaching-learning approach but to incorporate new tools and technologies that promote effective learning and facilitating continuous improvement (Bengu & Swart, 1996).

In this way, it is observed that despite the interaction students have with traditional machine tools, they arrive with a deficit that leads to the challenges faced by MSMEs. Thus, The Reconfigurable Micro Machine CNC Tool (Micromachine) emerged as a project capable of dealing with the challenges of structured processes and technological adoption required in the new manufacturing trends. It offers a platform based on an open hardware and software structure that responds to current manufacturing challenges such as modularity, line flexibility and project-based production to exchange modules in an agile way.

This project has a patent granted with the number MX / E / 2011/09375. It was born as a low-cost machine capable of developing different machining operations. The development of the first version of the engine was rudimentary and did not consider S^3 solutions in its design. However, the objective of reconfigurability and modularity was the central axis in its construction. As for now, this project pursues the aim of bringing a comprehensive insight into its value creation and deep market research to place it as a solid modular solution for education and MSMEs that cannot afford the costs of acquisition and maintenance industrial-graded machines.

Thus, the Micromachine is a didactic platform with professional capabilities to offer a certain degree of precision and to use both components and standard tools for its operation. In addition, modules have been developed to provide various functions with the same machine tool. Currently, it handles the modules of i) Lathe, ii) Milling, iii) Center Drilling, iv) 3D Printing, v) Food Extrusion, vi) Laser and vii) Plastic Extruder. New capabilities have also been explored, such as Cutter in the textile industry, Punching for braille engraving, Embossing for cardboard or plastic marking and QR code recorder on labels to condense product information.

However, this exploration of modules and different functionalities of the Micromachine would not have been possible without the redesign that began after taking the original patent for the machine and redesigning the Lathe module, which impacted the adoption of new solutions for the Micromachine. The S^3 Process Development RF reference model has been followed during this process, the results have been evaluated using the S^3 Scorecard. The following is a summary of the stages, activities and findings.

The case study was developed in a multidisciplinary manner. Therefore the previous requirements to solve the case study are detailed in table 5-5.

Table 5-5 Knowledge requirements to redesign the Lathe Module of the Micromachine

Development	Identified areas	Participant's profile	Relevant knowledge applied
Lathe module	Process engineering Industrial engineering Computation sciences Electronics Mechanics	Industrial chemical engineer Mechatronics engineer MSc manufacturing processes	Stress analysis in the axis of rotation Analysis of the variables of the manufacturing process of the lathe module Selection of standard components, brackets and tools for use on soft metals. Selection of instruments to control the speed of the module Numerical control software adaptation to switch between machine functions
Machine structure design	Industrial engineering Ergonomics Industrial design	Mechatronics engineer Industrial chemical engineer MSc engineering sciences	Design of an ergonomic structure for continuous use of the machine CAD and CAE of the structure with the maximum weights of the machine functions Transportable machine design Design of basic safety systems for the operation of the machine Modular bracket design to switch between functions

5.2.1 Definition of Manufacturing Process

The lathe is a mass reduction process. Its operation is based on the reduction of material from rotating figures on an axis. The use of tools allows the fracturing of the material or pickling to give shapes to cylindrical materials. It is one of the fundamental and recurring transformation processes in the industrial sector. The lathe is used in various applications. It is part of the primary curriculum in process engineering.

The Micromachine is a platform designed both for small-scale production and as a didactic tool in the training of undergraduate students, and their learning process includes a lathe module. The hardware must be in place to organize the module. It can be operated both manually and automatically using open source CNC software.

The Micromachine consisted of only three modules in its design, initially, lathe, drill and milling; however, early versions of the machine emphasized material savings and maintenance, but not the proposed solutions. The team's vision in charge has been enriched with the S^3 concept, and this vision is reflected today in the development or updating of the modules. Their configurations, materials and way of seeing the machine have been updated. Thus, it has become a didactic platform, but with precision to teach industrial machinery operation principles, modularity, flexibility, customization and operation at only one-quarter of what it takes to operate an industrial machine.

However, the inclusion of these solutions allowed the selection of suitable materials for the structure of the machine and the support of the different modules in the device, increasing its functions. In this case study, the redesign of the lathe module is presented. Therefore, a definition of its characteristics was carried out using the generic model of the lathe and identifying the attributes that describe the transformation. Relevant features were identified and summarized in Figure 5-4, to characterise the lathe module with the characteristics of the first version of the Micromachine.

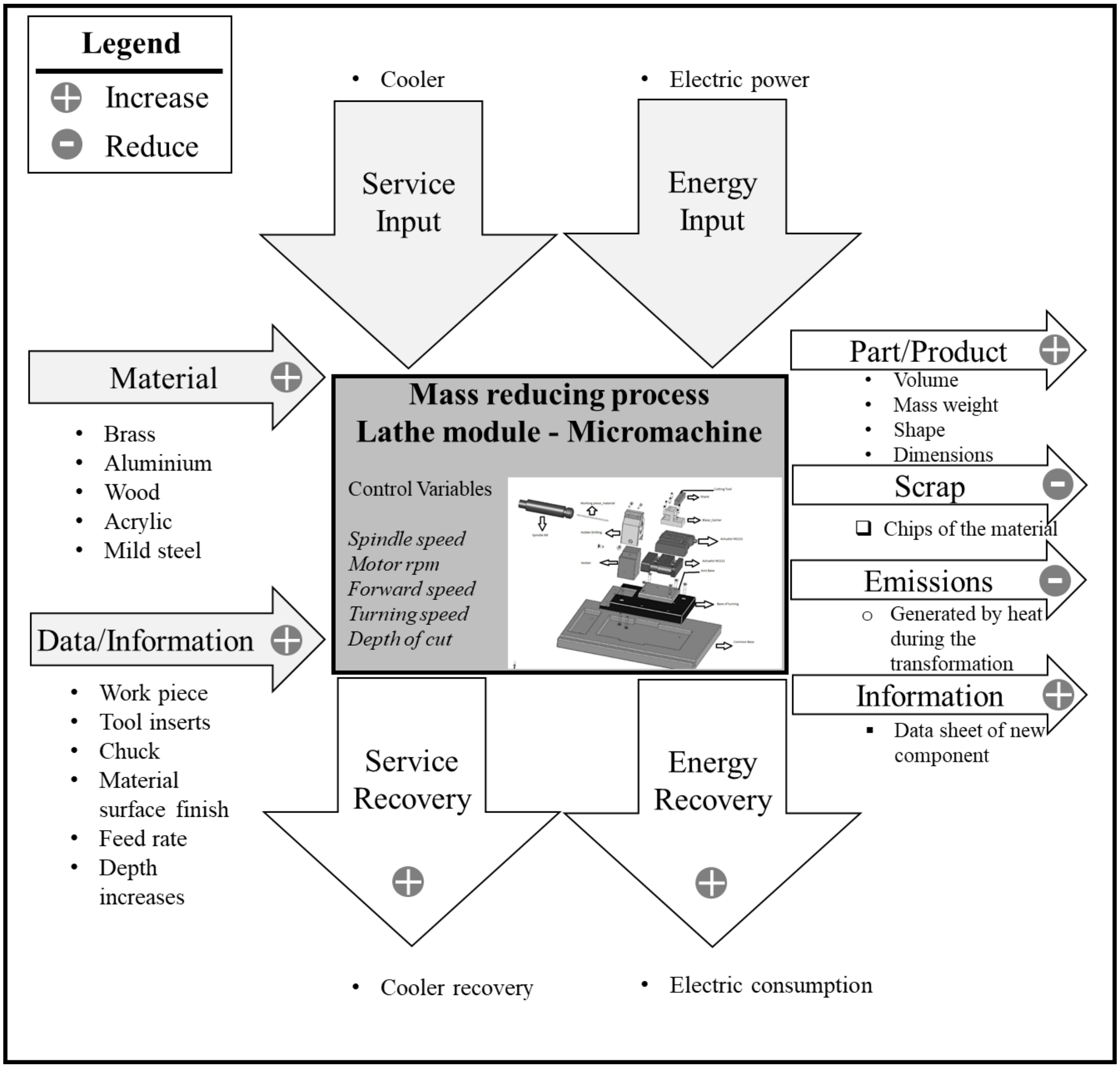

Figure 5-4 Generic model for the lathe module of the Micromachine.

Once the generic model has been generated, areas of opportunity have been identified to control the variables of interest, both in the transformation process and in the material, information, services and energy. There is an intention for designers to provide a module that incorporates the S^3 solutions to reduce the scrap and emissions generated by the process, recover energy and services, but above all, increase the productivity and information generated automatically in the module. For that purpose, the S^3 Process Development Reference Framework was used to lead to redesigning the module.

The taxonomy allowed defining the levels of the first version of the Micromachine, placing them at 1, 1 and 1 for Sensing, Smart and Sustainable solutions. The solutions included an external power source that allowed the speed of the spindle to be defined. It was not a comprehensive solution and was independent of the construction of the machine. Therefore, there was no management in the operation of the lathe. On the control side, the operator detected the irregularities of the module, which operated manually. Besides, the information was captured individually by the operator in question, thus depending on his skill and expertise in using tools and previous knowledge on the lathe. Regarding the sustainability of the module, there was an intention to reduce the waste generated by manufacturing. However, no prior study of the variables was carried out. In addition, the operation of various materials and a blur in planning made the collection of wasted material, mitigating sustainability in the production process.

Due to the interest of the development team in bringing this machine to market, it was necessary to include features to achieve a minimum viable product for both universities and MSMEs interested in its adoption for the creation of functional prototypes on a low scale. In this way, the module could not remain as the first version, and different adjustments to the structure of the Micromachine and its automation characteristics had to be rethought. Thus, with the use of taxonomy, the levels of automation of the product and the sustainable approach that should be promoted through the module of the perception of the Micromachine were defined. For the redesign of the lathe module, it was planned to scale the levels to 2, 2 and 2 in each of the solutions.

To achieve these levels, it was proposed to implement the solutions presented in Table 5-6. In this way, there would be control of the transformation and productivity variables of the process, an open-loop system capable of communicating information to the operator, to verify the operation or alert of problems, automating the operation of the machine and solutions by the part of sustainability to consciously reduce waste material and offer potential customers a recognizable added value to the efforts to generate both a didactic and professional platform on a small scale. There are presented an extract of the characteristics, solution and description planned before implementation.

Table 5-6 S^3 solutions in the lathe module of the Micromachine

Characteristic	Solution	Description
Sensing	Monitoring	• Cycle time • Presence sensors • Scrap is monitored • Energy consumption is monitored during the manufacturing process • Services are not calculated due to the type of materials used. They do not require a cooler
Smart	Control	• The lathe module is equipped with open-loop control • The position of the motors must be tracked through hardware and software • The raw material is registered to assess warehouse
Sustainability	Design	***Economic***: • Inspection of components is transferred to suppliers. ***Environmental***: • Eco-friendly components composition • Null hazardous materials • ROHS materials ***Social***: • Standard measures are considered for ergonomic production • Operators do less manufacturing using CNC software.
	Manufacturing	***Economic***: • Standard-based raw material and relative to size manufacturing reduce a high percentage of swarf. • Standard components reduce the need for additional features to fasten components • The maintenance of the module is reduced and packed easily • The operating station is easy to handle and monitor ***Environmental***: • Scrap material is planned to be disposed of for reusability • The tools and materials selected generate low emission manufacturing process • Energy consumption is monitored while manufacturing occurs ***Social***: • It reduces the impact on operators compared with the traditional production or similar products.
	End-of-life	***Economic***: • There is a deposition plan for the module ***Environmental***: • Tooling and materials are reusable • Waste from production is planned to be recycled ***Social***: • It does not apply

The description of the S^3 Solutions for the lathe module of the Micromachine became viable proposals to the subject of redesign that met the specifications of the mesoscale machines. These specifications are used to design similar products that are currently marketed, such as manual lathe machines, 3D printers, or milling machines for the industrial design area. Therefore, the breakdown of activities was continued to carry out the redesign.

5.2.2 Sequence of activities for the redesign of the lathe module of the Micromachine

To define the sequence of activities for redesigning the manufacturing process of the Micromachine lathe module, the Toolbox presented in Chapter 4 was used. The summary of the activities is shown in Table 5-7. Likewise, engineering activities were planned for each of the design stages. In this way, it is possible to assign tasks to the project development team and integrate the evidence into the defined tollgates of the project.

Table 5-7 Toolbox for the lathe module of the Micromachine

	Analysis	Synthesis	Evaluation	Tollgates
Individual Component Specification	**Identify Volume, Geometry, Material** Material databases Product data sheet Benchmarking Morphological matrix	**Determine availability, time and cost of components** Online suppliers Catalogue parts Material databases	**Select components and write down its specification sheet** Morphological matrix Functional decomposition Solution Matrix Bill of Materials	**Specification sheet of materials for the lathe module of the Micromachine.**
Manufacturing Process Selection	**Classify in the manufacture or standard parts** Electronic solutions Functional decomposition Standard component catalogues Sensor kit suppliers	**Determine a manufacturing or acquisition plan** Assemblies/ subassemblies of the manufacturing process Criteria success checklist	**Select machinery or suppliers** Process selector for the manufacturing components	**Definition of machinery needed, tools, supports and suppliers.**
Manufacturing Process Plan	**Identify time and cost for individual components** Material databases CES EduPack Part Cost Estimator	**Evaluate necessities against offers in the available market** Gantt Precedence Diagram Method	**Define a plan to achieve volume, quality, cost and time** Critical Path Method Identification of norms and standards Value Stream Mapping Cost analysis	**Specification of the manufacturing process for the lathe module.**
Evaluation of Manufacturing Process Plan	**Determine individual activities per station** Supply strategies Time and motion Capacity utilisation Equipment effectiveness	**Simulate different scenarios** Digital visualization The layout of the manufacturing plant Discrete Event Simulation using Tecnomatix Plant Simulation	**Optimise the manufacturing process plan** Evaluation of Discrete Event Simulation Assessment of Value Stream Mapping Deadtime reduction using optimization technique	**Manufacturing process plan evaluation**

The sequence of activities was presented to collect the most significant amount of information in each of the stages and for the evaluation to guarantee an adequate deliverable in each development phase. In this way, the redesign of the micromachine lathe module was conceptualised to include S^3 solutions in each of the stages presented. A group of developers can begin to carry out the activities individually. Their integration would result in the redesign of the manufacturing process of the lathe module to increase its automation levels and pursue an organizational objective that adds value to the potential customer and user.

5.2.3 Instantiation for the redesign of the lathe module of the Micromachine

The redesign of the lathe module of the Micromachine was carried out in parallel due to the need to explore various alternatives, dimensions of the solutions, construction material of the physical module and the response times of the suppliers, mainly of imported components, such as motors or slides to carry out the movement of the tooling towards the part. As previously mentioned, the proposed activities are alternatives to reduce the number of repetitions necessary in each stage. However, feedback is obtained during the implementation, especially for work teams incorporated into the performance. Even so, the BOM for component procurement plays a key role as it speeds up the process of procurement of work materials and staggered development of the module. The sequence of activities and the information obtained in each of them are shown in Table 5-8.

Table 5-8 Instantiation for the redesign of the lathe module of the Micromachine

Stage	Engineering Activities	Tools/Documentation
Individual Component Specification	*Identify volume, geometry, material* • Determine the measures of the materials as well as the motor capacity and support to process materials. • Identify the standard components available in the market for the construction of the module • Identify the cutting components and which materials it can produce. • Decompose the module in functions rather than materials and accomplish the desired functions • Define the required volume, geometry and material for individual components of the module. • Determine which sensors would be required to measure the process, productivity, energy, services and emissions. • Determine the initial array and where are they going to be assembled. • Identify the sustainable impact of the components according to the lathe process	• Material databases • Product data sheet • Benchmarking • Morphological matrix
	Determine availability, time and cost of components • Identify suppliers, similar components and viability to obtain components regarding the demand needed.	• Online suppliers • Catalogue parts • Databases
	Select Components and write down its specification sheet • Select components with the value-added characteristics needed • Choose sensors that allow arrays and that complement each other • There should be feedback among sensors to guarantee operations continuity. • Identify suppliers to cover the demand and generate a catalogue. • Write down the physical characteristics of the components as they are going to be used as restrictions when selecting the machinery	• Morphological matrix • Function decomposition • Solution matrix • Bill of Materials
Process Selection	*Classify in the manufacture or standard parts* • Classify the components in two groups: i) manufacture components and ii) standard components. Identifying the sustainable impact of the components • Determine which sensors are going to be direct, indirect, remote or wireless. • Determine if there is going to be an additional electronics solution that has not been considered previously.	• Functional decomposition • Standard parts catalogues • Electronic solutions • Sensors and processors kits
	Determine a manufacturing or acquisition plan • Standard components are acquired. Determine an acquisition plan with suppliers to deliver the parts strategically, reducing waiting time and assuring a continuous flow of material • Determine if there is going to be needed additional processes for standard components as finishing processes. Milling, Drilling, Cutting, Laser Engraving, among others • Manufacture pieces must be produced. There are two options during manufacturing components. The first one is to establish a sub-process where non-standard features are created; they are unique and adds value to products. The second is to establish a relationship with external manufacturers and determine the number of components to produce and deliver to satisfy the demand	• Checklist • Assemblies/Subassemblies
	Select machinery or suppliers.	• PRIMA Matrix • Process Selector

	• Select suppliers for those standard components. Special machinery for manufacturing processes. Select stations or machinery for finishing processes • Determine the location of the sensors to acquire electronic solutions with energy supply and restriction of temperature, among others.	
Manufacturing Process Plan	*Identify time and cost for individual components* • Determine material flow for assuring a continuous processing cycle • Determine packing and logistics for raw and finished products • Determine the cost of machinery, tools, commodities and additional services needed to keep ongoing operations • Determine the final sensors and smart processing units • Determine the sustainable impact of the components, electronics and processing units	• CES EduPack • Part-cost Estimator • Material Databases
	Evaluate necessities against offers in the available market • Verify the dimensions, finishing and effectiveness of components. • Identify the sustainable impact of the components • Compare the quality of the supplies against what would be offered • Compare the quality and lifetime of the sensor • Compare the processing units and lifetime • Compare the composition of the components sensors and processing units	• Gantt • Morphological matrix • Precedence Diagram Method
	Define a plan to achieve volume, quality, cost and time • Define production planning considering the volume of the products to be produced in the period defined • Determine the delivery periods and productivity calendar • Determine the quality parameters, processing time, number of operators, number of machines, cost and sale price. • Determine the duration of the machines to produce the module • Determine the impact of the sensors and processing units • Search for solutions with low impact • Determine the volume and cost to get the most value from components	• Critical path method • Value Stream Mapping • Identification of Standards • Life cycle Assessment • Cost analysis.
Evaluation of Manufacturing Process	*Determine individual activities per station* • Determine data and reports needed • Schedule shifts and individual tasks • Determine the number of operators and all supplies needed per station • Determine buffers and cycle times • Schedule maintenance of machinery • Schedule replacement for direct and indirect sensors	• Capacity utilisation • Supply strategies • Time and motion
	Simulate different scenarios • Use scenario-based techniques to represent different scenarios • Use Discrete Event Simulation to simulate operations of the manufacturing process • Simulate accurate distribution of the machinery • Include sensors and decision making in the simulation • Simulate failures of sensors and processing units • Simulate natural operation cycles with time	• Discrete Event Simulation • Digital representation • The layout of the manufacturing process
	Optimise the manufacturing process plan • Find optimal routes, number of workers, shifts • Find optimal cost • Find optimal S^3 solutions to achieve the initial planning of the manufacturing process • Fin optimal machinery	• Life Cycle Assessment • Evaluation of Discrete Event Simulations • Assessment of Value Stream Mapping

The redesign of the lathe module of the micromachine was carried out at the end of 2019. In the same way, the list of common materials for the elaboration of 4 Micromachines was included to generate a showroom in which the operation, modularity and flexibility of the device could be appreciated. The material was received, and the practical implementations were carried out until March 2020. Despite this, the instantiation of the methodology was carried out in the module. The summary of the redesign stages following the S^3 Process Development RF is shown in Figure 5-5.

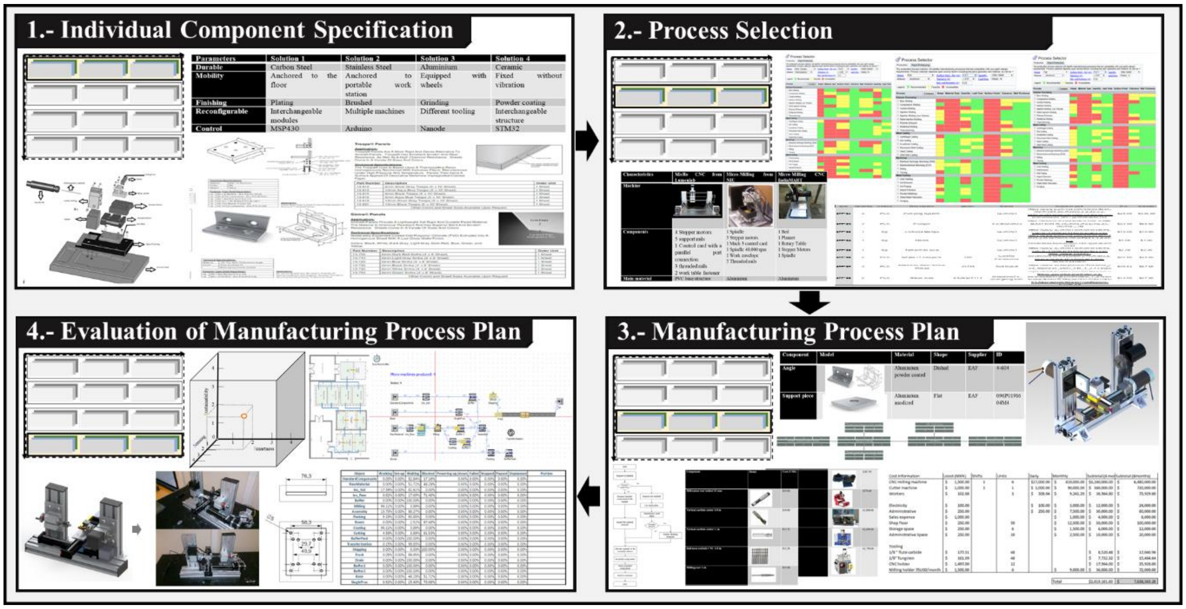

Figure 5-5 Summary of the lathe module redesign for the Micromachine.

The lathe module of the Micromachine represents a mass reduction process. The different solutions that were adopted had the purpose of increasing the automation of the module. In this manner, not only does the module work more efficiently, but the objective of taking this tool to a commercial level is pursued. The activities that have been carried out allowed the realization and documentation of the construction and utilization of the lathe module. The results and evaluation of the S^3 characteristics will be shown in Chapter 6.

5.3 Selection of S^3 solutions in the leak test process within an industrial production line

The S^3 Process Development RF seeks to bridge the gap between conceiving the manufacturing processes and the activities that must be carried out for their implementation. In this way, taking the methodology to real situations with manufacturing companies has been the intention of its construction. Throughout its development, it has had various total or partial applications, feedback in the design phases, engineering activities, and techniques or tools that make up the toolbox. The methodology was tested in controlled environments and laboratory tests. As the state of the art of the manufacturing processes grew, so did the construction of the model, with the ability to be instantiated from a few stages. At the same time, techniques such as creating virtual environments, data visualization and simulation through software were explored to exploit computational power in decision-making for industrial environments.

In this way, while the S^3 Process Development RF was being built, the author participated with manufacturing firms seeking joint solutions with the academy to solve real problems in the automotive sector. At the right time, the maturation reached both parties to carry out the implementation of the model in an industrial environment and measure the model's capacity outside the laboratory.

The manufacturing firm is one of the largest suppliers of auto parts in Mexico. Nonetheless, the times handled in industrial organizations far exceed the time dedicated to industrial research and the transformation phenomena that occur in these firms. Due to the strong influence of I4.0 trends, a department has been created in charge of exploring different technologies to adopt those that allow greater automation in decision-making to reduce accidents, work times, inappropriate postures, waste of resources and in general, make the processes carried out in its facilities more efficient. Even with this, the time of investigation and explanation of challenges is a constant for daily activities, so they have resorted to academia to explain specific processes and make efficient production decisions.

The first projects carried out between this tier one organization and Tecnologico de Monterrey were i) the analysis and monitoring of cutting tools in machinery, ii) a device capable of detecting faults and iii) exploration in simulation tools. In the three alternatives, technologies promoted by I4.0, communications infrastructure and computational power capable of processing historical or real-time daily operations data within the shop floor were explored. The exploration of simulation tools proved to be especially effective in creating scenarios, thereby reducing the organization's investment in physical tests and the work parameters that could be collated before their implementation. Thus, decision-making in the different phases of these simulation projects demonstrated the importance of this tool in an industrial environment. More tools began to be explored that would allow the explanation of increasingly complex models with accelerated development.

Initially, the simulation projects were to replicate a real scenario of manufacturing lines. A department was created within the organization that could replicate the work carried out and expand to the rest of the manufacturing lines. Later, multiple positions occurred on simulations with a platform of objects of the plug and play type, and the simulation time between scenarios was decreased. Inventory tools, flow control, warehouses, ergonomic studies and the possibility of reducing, recycling and reusing simulation libraries were explored.

The exploration of simulation tools led the organization to generate virtual models to explain the phenomena. However, real systems always have a degree of uncertainty, even with powerful software. In this manner, the organization detected a recurring manufacturing process in at least 80 per cent of its manufacturing lines that process aluminium parts. The leak test continued to pose a challenge for the physical explanations, the transformation process, and the simulation department.

The importance of this process led the department to analyse the manufacturing process to mitigate its uncertainty. This approach of the industry with the academy was necessary to carry out the analysis of the leak test and be able to make an effective decision making with the documentation of the process. However, given the magnitude of tests carried out within the organization and the investment that would imply keeping this process under control, a description of the phenomenon was chosen to explain the variables and the model that best it describes.

Although the requirement consisted of the recommendation to update the manufacturing process, to accomplish this objective in a successful manner, the decision was made to analyse of the capabilities incorporated in the manufacturing process, black-box model, grey box model, analysis of variables involved (Pintelas, Livieris, & Pintelas, 2020), and finally, make use of analysis, synthesis and evaluation activities for the incorporation of S^3 solutions in the leak test. In this way, the S^3 Process Development RF was used to describe the processes carried out, carry out a sequence of activities that represent the phenomenon, and carry out the instantiation to observe results in the manufacturing firm. As of the date of completion of this work, this project continues to be developed. However, the design, sequence of activities and instantiation have been defined for the leak test process. The partial result of this work is shown in this case study.

The case study was developed jointly between personnel from the industrial sector and graduate students. Therefore the previous requirements to solve the case study are detailed in table 5-9.

Table 5-9 Knowledge requirements to select S^3 Solutions in the Leak Test

Development	Identified areas	Participant's profile	Relevant knowledge applied
Leak test analysis	Thermodynamics Fluids Mechanics Materials	Mechatronics engineer Industrial chemical engineer	Analysis of the manufacturing process of the leak test Analysis of primary variables of the leak Thermodynamic analysis in the different stages of the leak test Heat and fluid flow modelling using CAD and CAE tools Design of experiments and statistical analysis of the controller response Computer-aided scenario generation Statistical data processing and analysis through software (R)
Instrumentation and control system recommendations	Control system Processing information unit Instrumentation	Industrial chemical engineer Mechatronics engineer Master in business administration Control and automation engineer Process engineer	Selection of relevant variables of the leak test through statistical results Instrumentation recommendation from simulation tools Modelling of variables to strengthen the controller process Development of a predictive system from historical data Critical variables instrumentation and testing in shopfloor

5.3.1 Definition of Manufacturing Process

Leak testing is widely used to detect dimensional or material abnormalities in finished and semifinished manufactured volumetric parts. This is achieved by i) introducing high pressurized fluid (commonly air) or ii) generating a partial vacuum to determine pressure changes in a given test time. This is a highly reliable and swift test to determine faulty parts. Nevertheless, the factors of pressure, temperature and volume create a correlation in which variations in any one of them affect readings. Thus, compensation is needed.

At the automotive tier one organization leak testing stations, fluid pressure is closely monitored with specific industrial controllers, whereas the volume of parts under testing remains constant. On the one hand, compressed air properties are not observed; thus, ambient temperature and humidity vary according to weather and daytime influence air quality. On the other hand, manufactured parts are mainly aluminium, a material with a high expansion coefficient due to temperature variations that could induce volume variability. The test cycle stages are structured to enhance measurements during the process.

Although the process remains homogeneous, there is an ongoing problem of reading accuracy on leak tests along with the work shifts, generating a large window of uncertainty to determine if parts comply with manufacturers specs. To reduce the latter, several workarounds are implemented. Wide range acceptability in the controllers and offset manual calculations are made on test stations to compensate for unknown transient fluctuations. This is time-consuming and needs trained personnel while the strategy is not automated and prone to errors.

Therefore, the leak test project is dedicated to characterising the variables, covariates and disturbances that interfere in the manufacturing process. This test constitutes a fundamental part of the quality of the manufactured products since it guarantees that the physical structure does not present any fracture in its composition. Therefore, their understanding contributes to adopting critical solutions to keep the process in an adequate working range during the operation. To carry out this analysis, automation concepts, descriptive execution techniques, and engineering activities will be used to support decision-making. The methodology to do so is S^3 Process Development RF.

The analysis of this manufacturing process, its components and thermodynamic interactions has been carried out by the Digital Factory Team of Tecnologico de Monterrey, using different techniques that allow supporting the decision to implement certain variables to keep the process within the parameters defined. As a case study, the leak test process will be analysed in a part of the manufacturing line located in Lerma. However, its generalization allows describing the general behaviour and the parameters in the different lines where the test is carried out.

The general objective was to generate an automatic reading compensation to reduce false positive or negative results during testing to fit process variables fluctuations along with work shifts. This can be achieved using different techniques that are hardware and software-based. The selection of one or both is dependent on the conditions of the installed equipment in the facility.

The leak test is performed within the manufacturing firm's facilities. However, conditions are adverse at various facilities. In other words, no temperature room allows the system's reproducibility, nor is there a hygrometer that will enable the analysis of humidity in the air supply line. In addition, the compressors take air from the environment, and the air transport lines are subject to temperature change since the pneumatic line feeds most of the processes. Due to the shape of the part and the moment the leak test is carried out, it is complex to obtain measurements of the cavities where the analysis is carried out. Also, filter systems have been explored, but it represents downtime in operation, and no significant improvement has been observed to justify its inclusion as an additional step.

Initially, a description of the black-box model of the leak test process was made. However, this analysis was discarded due to the variables that are outside the model. Therefore, an analysis of the generic model was carried out where the variables and co-variables that interfere in the manufacturing process are summarized. This characterization is shown in Figure 5-6, where the information to be considered during the test is reflected.

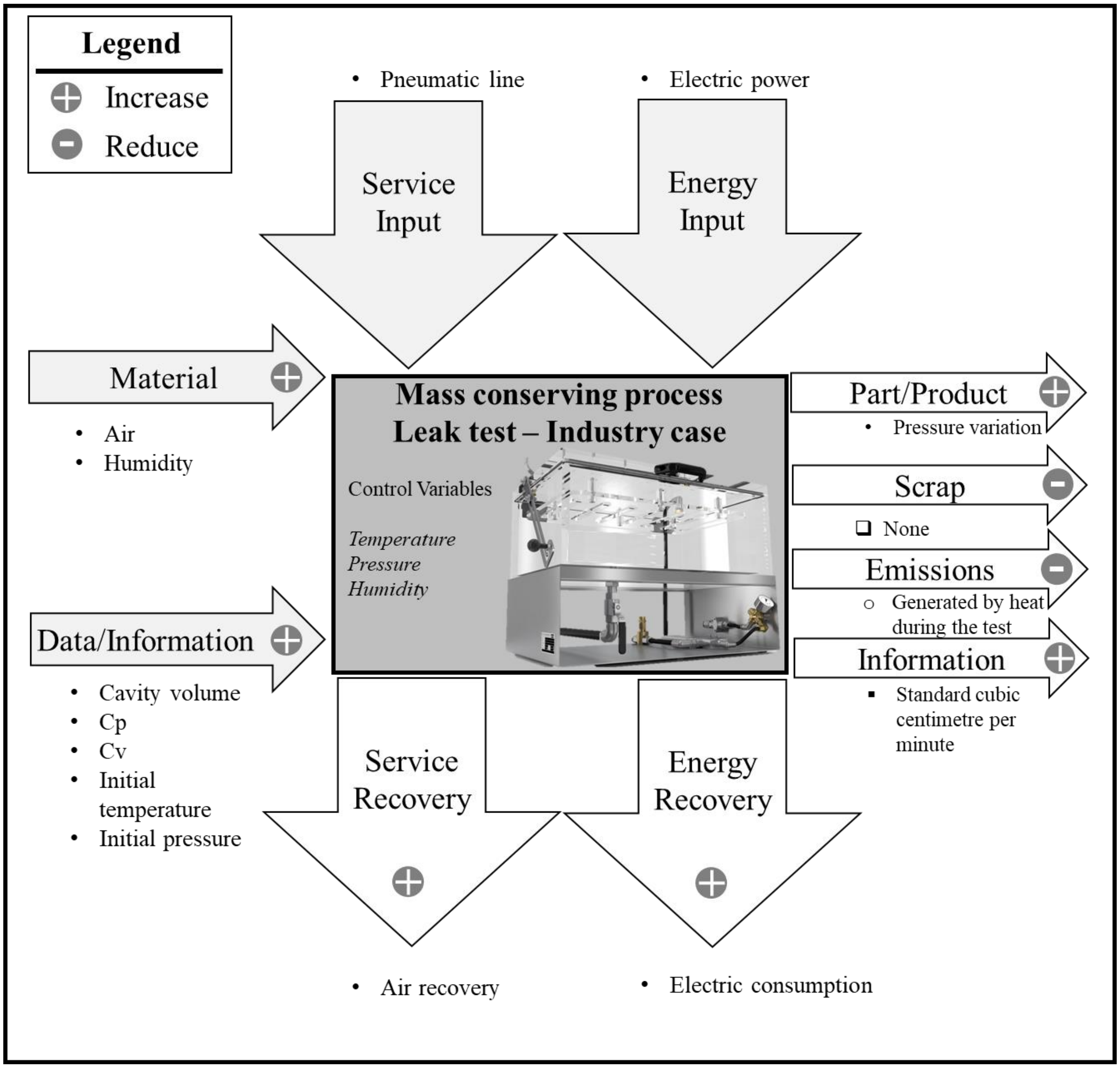

Figure 5-6 Generic model for the leak test.

To perform the leak test analysis, it was necessary to analyze the operating scheme of the system. The black box model was not sufficient due to the amount of information left out or considered a disturbance. This model is shown in Figure 5-7. Where the number of variables in green represents the critical variables, the yellow ones, the variables to be measured and the red ones the disturbances. Everything shown inside the dotted line means the closed system where the leak test is carried out, and the response is obtained from the pressure differential of the reference and the test part.

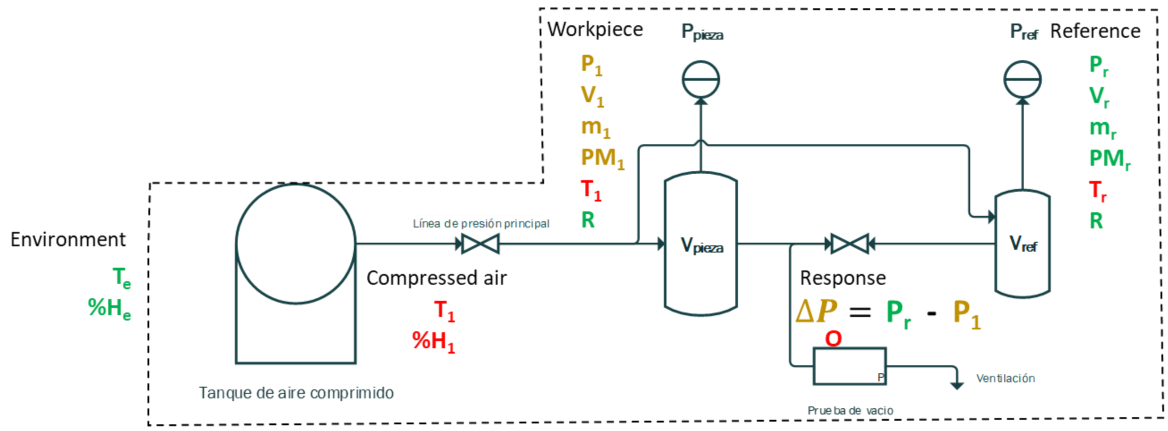

Figure 5-7 Black-box model of the leak test.

Although this was a first approximation, many of the covariates were discarded and what was initially called a disturbance actually carried more weight given the nature of the system. To fully describe the system, feedback from the manufacturing firm was necessary and historical data was obtained that would allow the process to be described from the plant point of view. In other words, a grey box model was created with a debugging of the critical variables and the covariates in 2 stages of the leak test process, where turbulent behaviour during filling and isochoric behaviour during the leak test is described. This model is shown in Figure 5-8.

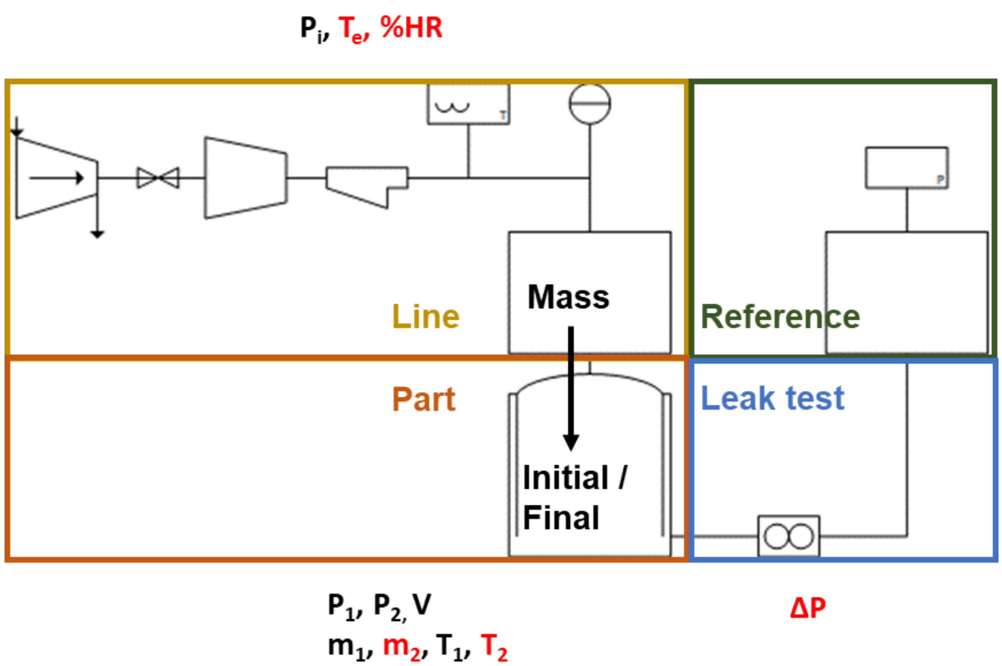

Figure 5-8 Grey box model of the leak test.

This model more adequately summarizes the information necessary to carry out the leak test and understand the variables involved in the system. With this representation, the generic model of the leak test was built. From these models, the critical variables of the system were understood, these being temperature, pressure and humidity. In the manufacturing line, these variables cannot be collected in their entirety. Hence, the need to describe the interactions of the model and the relevance of obtaining a response from them.

According to the leak test model, the S^3 solutions that would allow the description and analysis of the process in their entirety are described in Table 5-10. It is essential to highlight that those shown in the grey box model as red have not been registered and, therefore, are the project's objective to discern their relevance.

Table 5-10 S^3 solutions in the leak test

Characteristic	Solution	Description
Sensing	Monitoring	• There are sensors of pressure, temperature and humidity in the pneumatic line • There are sensors of pressure, temperature and humidity in the cavity of the working piece • Cycle time monitoring • Presence sensors of the working piece
Smart	Control	• The leak test is equipped with closed control • The processor is capable of comparing the setpoint and adjusting according to the temperature and humidity of the pneumatic line • The air enters free of humidity
Sustainability	Design	***Economic**:* • Compressors work efficiently with a known pressure along the line. ***Environmental**:* • Null hazardous materials • ROHS materials ***Social**:* • Standard measures are considered for ergonomic production
	Manufacturing	***Economic**:* • The pneumatic line does not introduce humidity to the leak test ***Environmental**:* • There is no scrap during the leak test • Energy consumption is monitored during the leak test • Emissions of the leak test are collected and treated. ***Social**:* • It reduces the impact on operators compared with the traditional production or similar products.
	End-of-life	***Economic**:* • There is a deposition plan for the machine • All materials are recycled ***Environmental**:* • All materials of the machinery are reusable • Waste from production is planned to be recycled ***Social**:* • It does not apply

The series of solutions was reviewed by the personnel of the manufacturing firm in contact. Tests were agreed to define the impact of the solutions and to be able to discern between alternative solutions to implement in the manufacturing lines. Therefore, the description of the S^3 Solutions for the leak test became viable proposals to explore. Thus, the sequence of activities that was defined for incorporating these activities in the leak testing process is described in the following section.

5.3.2 Sequence of activities for the leak test

To define the sequence of activities for the introduction of S^3 solutions in the leak test, the Toolbox presented in Chapter 4 was used. The summary of the activities is shown in Table 5-11. Likewise, engineering activities were planned for each of the design stages. In this way, it is possible to assign tasks to the project development team and integrate the evidence into the defined tollgates of the project.

Table 5-11 Toolbox for the lathe module of the Micromachine

	Analysis	Synthesis	Evaluation	Tollgates
Individual Component Specification	**Identify Volume, Geometry, Material** Thermodynamics of the system Variable decomposition Black-box model Grey box model	**Determine availability, time and cost of components** Definition of the type of system	**Select components and write down its specification sheet** Type of system that describes the leak test	**Specification modelling based on physical phenomena of the leak test**
Manufacturing Process Selection	**Classify in the manufacture or standard parts** Cavity volume database Historical data analysis	**Determine a manufacturing or acquisition plan** Data analysis of humidity Data analysis of temperature	**Select machinery or suppliers** Finite element modelling	**Equations that describe the leak test model**
Manufacturing Process Plan	**Identify time and cost for individual components** Catalogue components Supplier of pneumatic line instruments	**Evaluate necessities against offers in the available market** Psychrometric analysis of the solution	**Define a plan to achieve volume, quality, cost and time** Response surface of the temperature and air humidity	**Specification of the sensing solutions for the leak test.**
Evaluation of Manufacturing Process Plan	**Determine individual activities per station** Design of Experiments for humidity, temperature, cp, cv and pressure response	**Simulate different scenarios** Response surface analysis Response surface simulation	**Optimise the manufacturing process plan** Statistical data analysis Instrumentation recommendations based on analysis	**Sensing solution evaluation and instrumentation proposal**

The sequence of activities for this case was used to describe the model according to physical behaviours, discern the critical variables, covariates and disturbances present in the system that have impact in the measurements, obtain a model, specify the type of sensing solution, and evaluate various alternatives to perform a control proposal aligned to the needs of the organization. The same four stages of design of a manufacturing process entity were followed. The detailed description of the analysis, synthesis and evaluation allowed to summarize the activities to be carried out in a more specific environment because the case study warranted it. Taking into account the S^3 Solutions and the sequence of activities, they proceeded to instantiate them to include them in the leak test.

5.3.3 Instantiation for the incorporation of S^3 solutions in the leak test

As could be seen in the section on the definition of the manufacturing process in this case study, a level to be achieved was not selected for any of the S^3 solutions. This is because the system already has most of the solutions, and only advice is required in discerning the variables that are not critical. The leak test is carried out on an automated instrument. However, the lines where the test is carried out are not; therefore, the project was requested. The instantiation of the sequence of activities has a different purpose than that of the design or redesign. It is more about refocusing the leak test instrument's capabilities to select the variables with the highest degree of interference in the process. Then, propose a control model that is general in all its manufacturing lines. By instantiating the instruments in the leak test, the information in Table 5-12 was obtained.

Table 5-12 Instantiation for the incorporation of S^3 solutions in the leak test

Stage	Engineering Activities	Tools/Documentation
Individual Component Specification	*Identify volume, geometry, material* ・Determine the physical laws that govern the leak test ・Determine which are the variables of the system ・Determine the covariates ・Determine the disturbances ・Determine the response of the leak test ・Determine the cavity volume ・Identify which are the laws that describe the process	・ Thermodynamics of the system ・ Variable decomposition ・ Black-box model ・ Grey box model
	Determine availability, time and cost of components ・Identify different systems with a similar response ・Identify interaction between variables ・Identify interaction between variables and covariates	・ Definition of the type of system
	Select Components and write down its specification sheet ・Select the model with the least amount of variables that explain the behaviour ・Select the model with physical but explainable restrictions ・Determine which is the ideal model ・Determine which is the real model	・ Type of system that describes the leak test

	• Identify what causes reality behaviour	
Process Selection	*Classify in the manufacture or standard parts* • Identify the range of cavity volume of components where the leak test is executed • Identify the tolerances of the cavities • Identify typical deviation in the cavities	• Cavity volume database • Historical data analysis
	Determine a manufacturing or acquisition plan • Discern between humidity and temperature variables in the leak test • Analyse historical humidity in the region • Analyse historical temperature in the region • Determine the thermodynamics relationship when air is humid • Analyse the properties of wet air	• Data analysis of humidity • Data analysis of temperature
	Select machinery or suppliers. • Discern between variables • Discard the material transfer heat to the air in the cavity section of the working piece • Discard or prove the interaction between humidity and temperature when air presents humidity • Analyse the impact of the humidity in the system • Analyse the temperature against humidity variables	• Finite Element modelling
Manufacturing Process Plan	*Identify time and cost for individual components* • Identify catalogue components for humidity or temperature • Consult an alternative for pneumatic line instruments with the organization's supplier • Discard features that are unfeasible or not cost-effective • Analyse choices of sensing solutions	• Catalogue components • Supplier of pneumatic line instruments
	Evaluate necessities against offers in the available market • Identify psychrometric behaviour of the system • Analyse psychrometric region of the historical behaviour of the leak test • Analyse typical humidity and heat capacity of the process	• Psychrometric analysis of the solution
	Define a plan to achieve volume, quality, cost and time • Determine the response surface between humidity and temperature of the leak test analysis. • Determine the behaviour of increasing temperature of entrance • Determine the behaviour of the response surface when increasing the humidity • Determine which variable has the most errant behaviour	• Response surface of the temperature and air humidity
Evaluation of Manufacturing Process	*Determine individual activities per station* • Create a standard table for the design of experiments considering the humidity, temperature, cp and cv of the system • Create multiple scenarios with a high and low range • Generate multiple responses that emulate the historical behaviour of the leak test • Identify the distribution of the data • The design of experiments must cover the full range of data	• Design of experiments for humidity, temperature, cp, cv and pressure response
	Simulate different scenarios • Use scenario-based techniques to represent different scenarios • Use statistical software to simulate operations of the manufacturing process • Simulate accurate distribution of the leak test • Simulate extreme values of the range • Describe the statistical behaviour of the system	• Response surface simulation • Response surface analysis
	Optimise the manufacturing process plan • Find an optimal model with the design of experiments of the leak test analysis • Create a set of recommendations for instrumentation purposes using statistical data analysis • Evaluate the alternatives of instrumentation	• Statistical data analysis • Instrumentation recommendations based on analysis

The inclusion of the S^3 solutions within the leak testing process constituted the implementation of the S^3 Process Development RF. The activities served to document the process of discarding the different variables that were initially considered. The constant interaction with the manufacturing firm's engineering group helped clarify the issues that were not evident and served as evidence that certain variables had more significant interaction than others during the operation of the leak test. Thus, both parties were able to observe the development and implementation of activities gradually and under the findings that arose at the end of the same. Evidence of the instantiation process is shown in Figure 5-9.

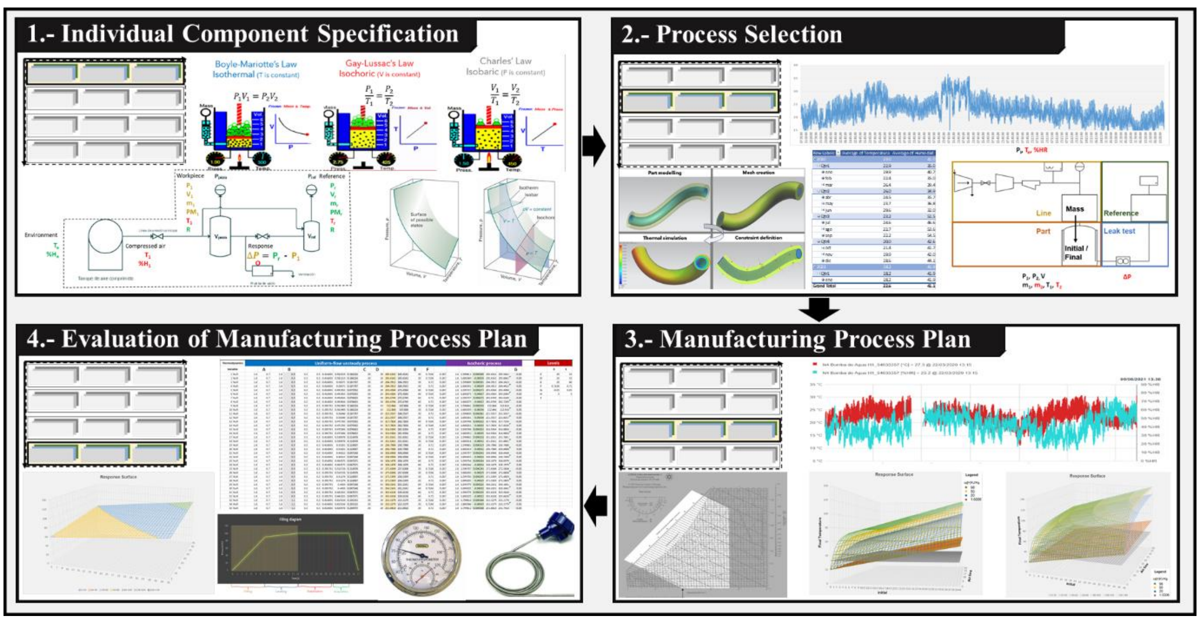

Figure 5-9 Summary of the activities for the leak test using the S^3 Process Development.

The leak test is an activity that must be carried out to guarantee the safety of the parts produced. It is carried out with a calibrated standard, and the pressure difference allows measuring its efficiency. However, it is susceptible to modifications during the day, given the nature of the fluid with which it is carried out. Therefore, it is necessary to identify which are the variables with the highest degree of interaction in the process and which variables to implement to ensure that the test is controlled. For this purpose, the S^3 Process Development RF was used to discard variables with a scientific basis. The results and evaluation of the S^3 characteristics will be shown in Chapter 6.

Chapter 6 Results and Discussion

This section shows the results and evaluation of the S^3 characteristics of the case studies of manufacturing processes presented in Chapter 5. Because each of the cases was carried out from the methodology presented in Chapter 4, the particular results can be extended to a general analysis of the application of both the Taxonomy and the S^3 Process RF, using tools to complete the engineering activities of the process.

This chapter will show the results in a condensed form of the evaluation of the manufacturing process. An own analysis to measure the level of the S^3 attributes in manufacturing processes called S^3 Scorecard and an outline of the characteristics as well as a summary of the critical features of the S^3 Process at the end of each project.

Subsequently, the discussion of the general results of the S^3 Process RF in the industrial context will be addressed. The objectives of this study will be compared with the hypotheses raised at the beginning of the work.

6.1 Results

6.1.1 3D Food Printer results

The design of the machine corresponded to levels 2,2,2 in each of the Sensing, Smart and Sustainable solutions, respectively. At these levels, the following characteristics would be obtained:

- Sensing. Not only is the process equipped with sensors that make it possible to measure the control variables that govern the process, but also productivity variables and involves a series of sensors that allow the information to be triangulated to have more precise measurement parameters.
- Smart. The control system is open-ended. It is based on interaction by detecting system variations and issuing basic actions that allow the parameters obtained from the Sensing solution to be compared with the set point. The aim is to implement the

system, but the manufacturing process works within a range and is operated manually in the event of any variation detected outside it.

- Sustainability. At this level, sustainability is explored as a form of organizational differentiation. The processes are selected to reduce scrap, and it seeks to take maximum advantage of the energy. However, no action is taken to reduce its consumption. The services operate fundamentally. They are used for several runs in the process, and emissions can be detected, more they do not represent an effort to attract or reduce them. The most impacted dimension is the economic one by directly decreasing the material wasted during the operation and making the most of the raw material.

Once the 3D Food Printer development was carried out, levels 2.20, 2.20 and 2.20 were obtained in each of the S^3 solutions. In Figure 6-1, there are observed the parameters to be considered in each of the characteristics adopted, in this way, it is possible to break down the level obtained with the parameters that best describe the feature since partial solutions can be assumed and achieve a higher or lower level depending on the devices.

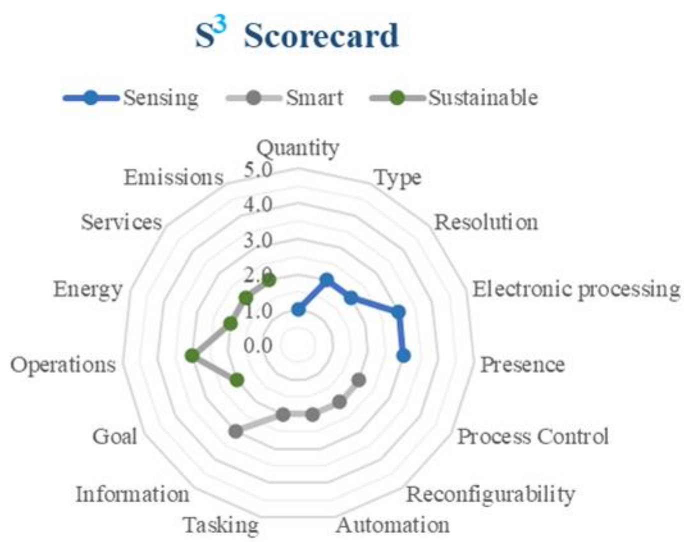

Figure 6-1 S^3 Scorecard for the 3D Food Printer.

The evaluation of these individual parameters was carried out in the S^3 Scorecard tool that allows visualizing the solution based on the commercial solutions.

Finally, Figure 6-2 shows the general process of the activities carried out and the summary of the development results on the right side.

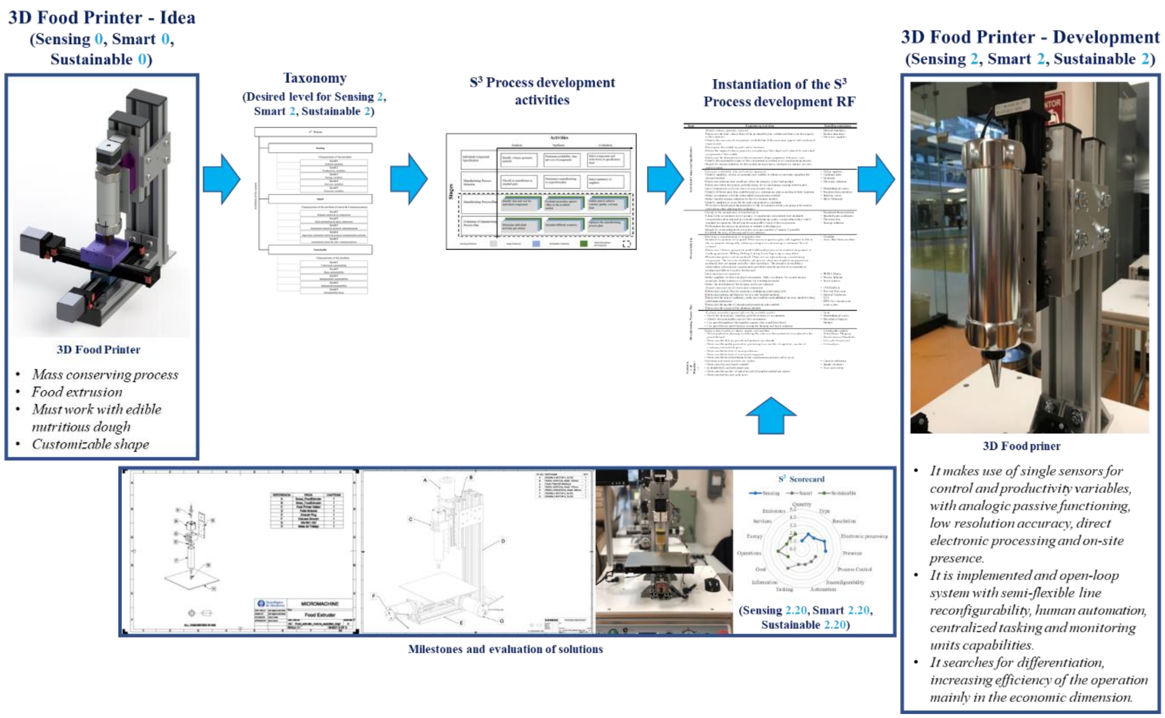

Figure 6-2 Summary of S^3 characteristics implemented in the 3D Food Printer.

The development of the 3D Food Printer was carried out satisfactorily and with the support of a multidisciplinary team between Universidad de Los Andes and Tecnologico de Monterrey. Implementing the S^3 Process Development RF made it possible to develop a transformation process according to the new manufacturing currents, above all, aligned with I4.0 and SDGs.

6.1.2 Reconfigurable Micro-Machine Tool results

The redesign of the lathe module of the Micromachine contemplated levels 2,2, and 2 of each of the S^3 Solutions. However, once the process was concluded, an evaluation was made of what was implemented before the global crisis derived from COVID-19. The levels reached in each characteristic were 2.20 for the Sensing solution, 2.60 for the Smart solution and 2.0

for Sustainability. Exceeding the levels proposed by identifying the initial characterization attributes of the lathe module.

The level of Sensing was mainly due to the selection of solutions with low resolution but high precision and repeatability when taking the measurement. The increase in the Smart level derives from the reconfigurability offered by the Micromachine and the ability to reuse the machine and the communication module. This allows data to be communicated to the CNC software regardless of the function used in the machine and to have partial automation processes, only indicating to the software which module it is. In this way, greater efficiency is obtained with the acquired module and allows better monitoring and processing of the quantities collected. Finally, the Sustainable level was kept at two since it pursues a differentiation objective that the potential client or user can perceive, it promotes increased efficiency, by having encoders in the machine's motors, the material has a better response from its position, being able to measure the amount of rough material.

At the end of the Micromachine mass reduction process redesign, the evaluation of the adopted S^3 Solutions was carried out. In Figure 6-3 there are presented the features evaluated in each of the levels.

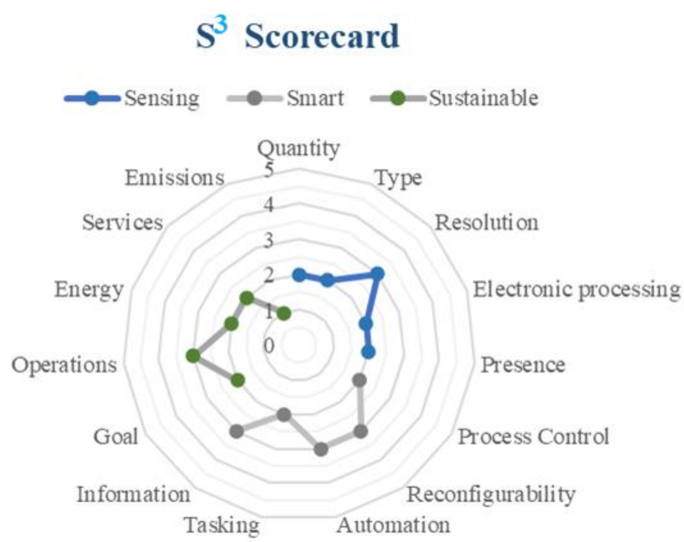

Figure 6-3 S^3 Scorecard for the lathe module of the Micromachine.

The redesign of the lathe module of the Micromachine was carried out to update the technology and increase the flexibility and modularity of the device. With this, a product was obtained in which it is possible to carry out laboratory tests or transport it to the field to carry out tests with Potential users. However, documentation work still requires materials' use and processing capabilities to generate a didactic platform with evaluated educational practices. Even with this, the result was positive and showed improvements following the solutions acquired that can be reused by other modules, increasing the machine's functions. Figure 6-4 shows a summary of the process carried out to redesign the lathe module of the Micromachine.

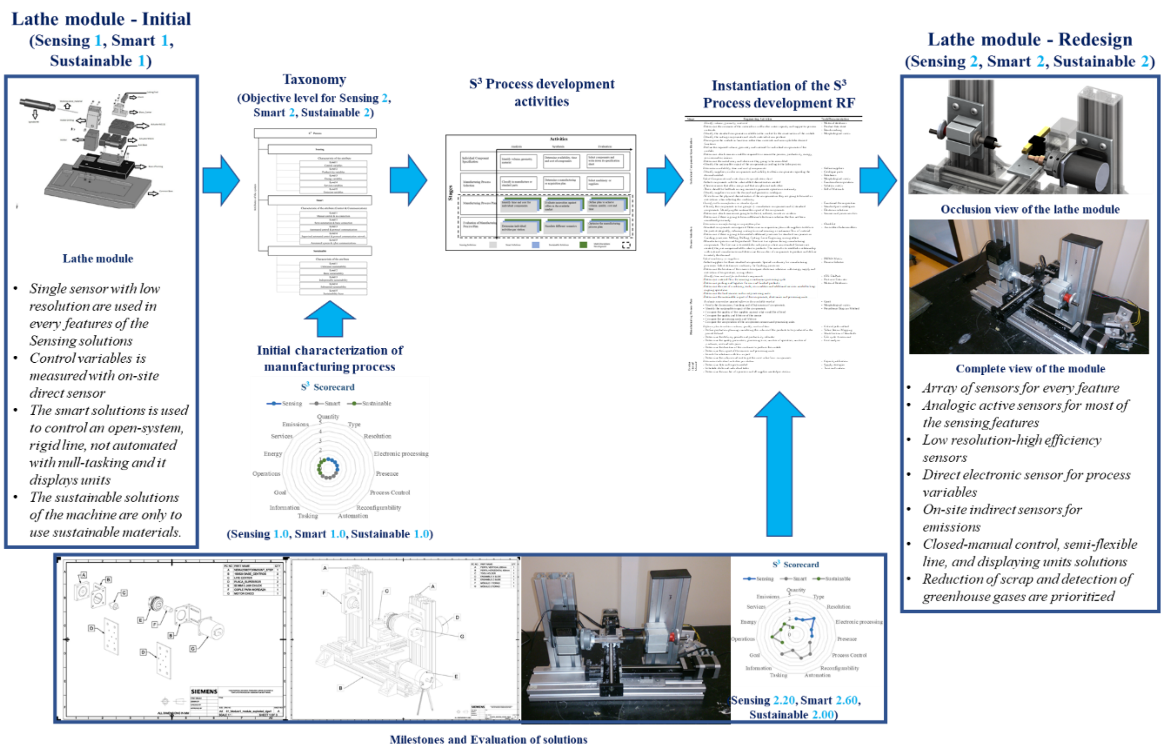

Figure 6-4 Summary of S³ characteristics implemented in the lathe module of the Micromachine.

The redesign of the micromachine lathe module was just the beginning of a series of updates made to the platform. By including solutions that seek to automate manufacturing processes, the general design of the Micromachine was strengthened. The objective of the product aims to offer a didactic platform for the educational sector. However, it has professional capacities that can be used in different engineering projects. In this way, the possibility of having other potential customers and reaching different markets is opened, such as entrepreneurs, enthusiasts of the DIY movement and MSMEs that intend to develop functional prototypes on a small scale or test the operation of specific components quickly. Implementing the S^3 Process Development RF made possible the redesign of an essential transformation process in the manufacturing area for a platform that aims to offer a solution mainly to students, bringing practice closer and making it affordable for institutions.

6.1.3 Leak Test results

At the beginning of the project, the leak testing process within the manufacturing firm had levels 3.80 for Sensing, 3.80 for Smart, and 3.40 for Sustainable. A highly automated process aligned with the organization's policies for sustainable growth. The Sensing and Smart levels work together to offer highly automated processes, capable of executing complex tasks and monitoring machine operation from test start to completion. At the same time, the Sustainable level emphasises serial processes that meet a specific objective and do so making the most of resources. The individual characteristics of the solution are summarized in Figure 6-5.

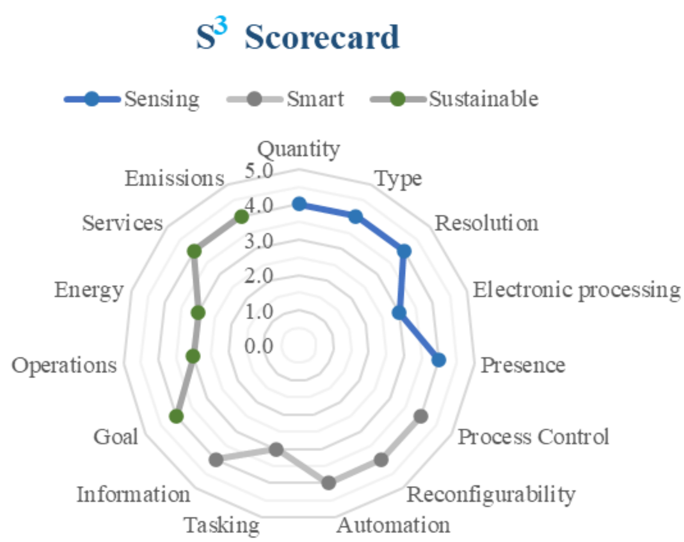

Figure 6-5 S^3 Scorecard for the leak test

This project consisted of implementing the S^3 Process Development RF not to increase the levels of the solutions, but to be able to select the appropriate control variables to keep the process as stable as possible throughout the day and in any region where the leak test takes place. Therefore, the expected level at the end of the instantiation should have remained intact. However, the implementation of the methodology contributed to the decision-making process and documentation of the crucial variables in the process to be implemented. Therefore, in the same way, the sequence of activities typical of the methodology was carried out, but modifying the tools allowed to delve into the particular behaviour of the leak test. Both parties agreed with the activities that were carried out, and the progressive way in which they demonstrated the relevance or not of certain variables allowed the manufacturing firm's team to understand the behaviour explained by the academy team. Figure 6-6 shows the starting and ending point of the project and critical milestones that allowed the demonstration of certain physical phenomena for the description of the leak test analysis.

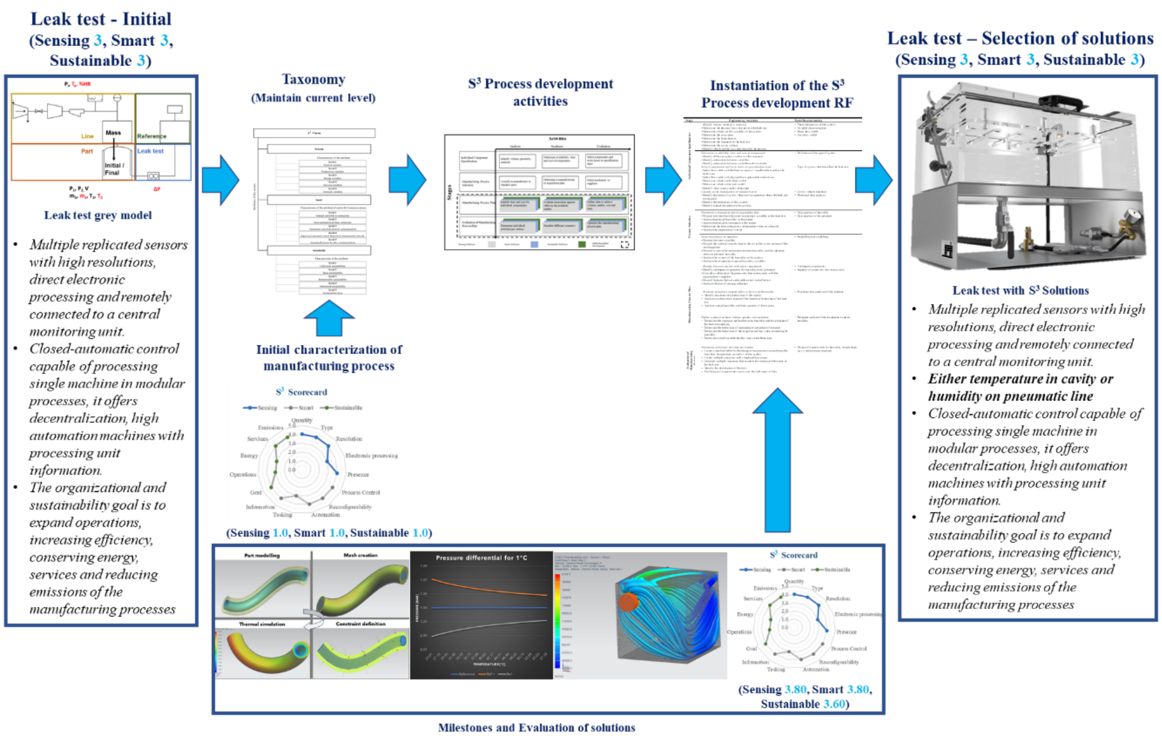

Figure 6-6 Summary of S³ characteristics implemented in the leak test.

The result of the project by the simulation team culminated in two possible strategies for the manufacturing firm. i) Instrument the pneumatic line with a hygrometer. This solution would allow controlling the psychrometric process that is carried out during the filling of the part and predict the behaviour of the gas inside, which would result in the correction from the humidity inside the cavity, obtaining repeatability in the leak test. Or ii) instrument the cavity of the workpiece to measure the temperature inside it. This proposal makes use of the specific heat properties contained by the fluid inside the part. It allows the reverse process of proposal one to be carried out to allow the correction of the control module that executes the test. Both solutions were explored from the statistical point of view, with this, both solutions would allow obtaining the mathematical model to introduce in the current controller of the leak test. The choice was pending by the company to analyze the most suitable alternative in all their aluminium manufacturing plants.

6.2 Discussion

Different findings can be observed from the results obtained when applying the S^3 Process Development RF. The following is listed according to the relevance of the research questions that originated this work. These generalizations are generated from the results of the case studies.

1. **Generic manufacturing process model.** The generic model collects information about the relevant variables to consider to automate the of a manufacturing process. In this manner, manufacturing process developers, operators, and decision-makers can easily recognize the variables to consider and invest to accomplish organizational goals. Hence the importance of outlining the generic model at the beginning of the design, redesign or characterization of the manufacturing process in question. At this stage, it is possible to glimpse the inputs and outputs of the manufacturing process with its own control variables.

2. **Taxonomy.** The use of the S^3 solutions level taxonomy is not intended to be the automation standard for organizations. Nevertheless, it is designed to guide designers who wish to characterize a manufacturing process, design objectives, or organizational objectives that dictate what resources to invest in increasing manufacturing processes' automation or reaching new levels of remarkable sustainability in transformation processes. In this case, the taxonomy works as an enabler of design goals. This approach makes it possible to identify which devices to invest in to have a more Sensing process, or what type of processors to implement to increase the processing or communication of information, but above all, which

variables of the generic model will have more weight, aligned to the organizational objectives to increase sustainable goals and with it the perception of value for customers, consumers and society.

3. **S^3 Process Development Reference Framework.** Besides, the activities for the design and implementation of a manufacturing process are presented in the S^3 Process Development Reference Framework. Which presents design stages in a structured way along with specific engineering activities in each stage, thus, it is possible to instantiate according to the manufacturing sector and document the development. The instantiation of the activities in the manufacturing process provides an overview not only of the operation of the transformation process and its constraints but of automation solutions and sustainable objectives by the organization. In this way, adopting S^3 solutions allows conceptualizing the manufacturing process as an entity with a beginning of life, an operational stage and a final cycle of operation. With this in mind, solutions must be adopted considering these life cycles of manufacturing processes to increase automation, but at the same time think about the economic, environmental and social dimensions that they imply.

4. **Toolbox.** The sequence of activities makes use of different design tools. The engineering actions of analysis, synthesis and evaluation function as a structured guide to approaching design stages. In this way, the implementation is carried out in an agile way, but during the process, the documentation for decision-making is obtained throughout the selection of tools from the Toolbox proposed for industrial sector. The development constitutes an iterative process. This can be clearly observed in the development of products and the interaction with the end customer; however, for the manufacturing processes, this feedback does not have an end-user with whom to contrast the result. Instead, it uses tools that allow more information to be consulted before evaluating and selecting solutions. Hence the importance of structuring the engineering activities together with the tools allows having a notion of what will be obtained at the end of the design stage and allows to assign individual tasks to the development team.

5. **S^3 Scorecard.** The S^3 Scorecard is a tool developed to show the degree offered by the adopted solution. That is, it would be useless to fill a manufacturing process with sensors that allow detecting the presence of raw material at all times. The number of sensors could be increased; however, it would not add value to the manufacturing process unless that information can be processed somehow. It becomes vital to know the position of the materials in real-time. Then, a solution can be evaluated with the installed capacity and the precision, resolution of the components, tolerances that it offers, and operating conditions in which it can offer a response. The set of these solutions and the quality and clarity with which information can be obtained from them make it possible to increase the level of the solutions and, consequently, of the system. The evaluation tool thus allows knowing the degree of the solution implemented in the manufacturing process.

6. **Methodology**. The contribution of this work is not intended to be an extensive compendium of the various existing manufacturing processes since each has a particular way of functioning, control variables, physical applications or material restrictions; however, it does intend to collect these individual characteristics and present them to establish a methodology for the development of manufacturing processes. The methodology as a whole seeks to identify the solutions of the current manufacturing processes, define organizational objectives for automation or perception of value and carry out the sequence of activities to reach new levels of production or reaffirm the purposes of the manufacturing firm. It is a tool that condenses the existing knowledge of the manufacturing processes developed and allows adding value to the entity in charge of generating value in the industrial sector. Any existing system has some level of S^3 characteristics. However, the evidence of these functions clarifies the variables of greatest interest to organizations and allocates resources to those that allow increasing value within the manufacturing firm.

Verifying the increased S^3 levels allows measuring the efficiency of the design process, redesign or characterization of the current solutions. Hence the importance of carrying out the planning, objective and implementation of the methodology in the proposed sequence of activities. In this way, it is possible to allocate a budget to solutions that allow increasing the organisation's value through automation or seeking economic savings in terms of the use of materials. Thus, the gap between the creation of manufacturing processes and a methodology that allows identifying the areas of opportunity for an organization of any size is narrowed through the use of S^3 Process Development RF. The current challenges of organizations involve adopting technologies, using resources, and optimising production processes. However, this process does not have a valid structure in all stages of the business. Despite having defined objectives with current industrial currents, the process to achieve them constitutes a challenge today. These challenges mostly correspond to the structure to adopt technology and the operation of the activities within its facilities. This work aims to reduce the effort and time dedicated to investing in solutions that could not generate value within the organization and target those that have the most significant interference in the organization's manufacturing processes.

Chapter 7 Conclusions

In this section, the conclusions of the work are explored as a set, according to the motivation, justification and research questions presented at the beginning of the dissertation.

7.1 Conclusion

The I4.0 concept brought various guidelines for creating highly efficient systems, taking advantage of the communications infrastructure of organizations, automated technological tools, and the increasingly growing computational power that has been adapted to different sizes and layers of operation. The efforts of the organizations demonstrated the ability to adopt technology; however, it did show resilience, especially in the workforce. Therefore, this utopian concept evidenced the lack of structure for manufacturing migration's creation, execution, and end of life, especially in the transformation processes. Soon, this theme became recurrent in the industrial sector, and large organizations were using exploration tools to adopt new solutions. However, the efforts were not enough since the market was now also communicated and was participating in a revolution of consciousness to decide what to tolerate or not and precisely, differentiators in the perception of the market were required to acquire what the industry offered. How the industry did the products mattered more than the sector contemplated, and the race to introduce products became a constant. The gap in this competition began to widen in all sizes of industry, and in this way, an area of opportunity for the investigation and explanation of the phenomenon arose. The problems in implementing the I4.0 concept were identified as lack of structure, technological adoption, and implementation of solutions in processes that required to be increasingly agile and with a modular distribution to offer customizable features to an increasingly demanding market, evidencing the lack of skills to understand the needs, but pressing with the loyalty towards the organizations. For the first time since the beginning of the industry, this phenomenon was seen in which the user became a prosumer and participated in real-time of what he wanted to consume. This gap in communication, introduction to the market, agility, technological adoption and productive capacity is still looking for an answer.

It is precisely these questions that shaped the work described. Areas of opportunity were identified in how processes are done today, most of them are preserved with traditional, semi-automated but individual machinery, best practices dictate a degree of automation in key manufacturing lines for organizations, so it has become a strategy in which to invest to cover the increasingly global markets. Likewise, at present, few methodologies focus on the design of manufacturing processes. There are standards mainly focused on management systems, but they do not dictate a structure to follow. However, the reference models for the design of manufacturing entities and the concept of Sensing, Smart and Sustainable have provided a solid base to contribute to this problem and address the industry's needs.

In this work, a methodology that contributes to the development process of manufacturing processes is presented. It emphasizes the adoption of both automation characteristics and sustainable organizational objectives. The complete development involves i) the sketch of a generic model to distinguish between the variables with greater importance in the manufacturing process, ii) the identification of the S^3 concept and define levels of objectives in the design or redesign of the manufacturing process, iii) the definition of the sequence of engineering activities, the definition of tollgates and tools or standards that apply in the sector to be developed, iv) the instantiation of the activities in the defined context and v) the evaluation of the solutions adopted. With the results obtained from the case studies, contributions and discussions in 6.2, it can be concluded from this work the following.

1. The graphic presentation of a manufacturing process helps in the process of defining critical variables. In addition, this scheme allows to design, redesign, or select technology or materials available in the market to increase the manufacturing process's automation or sustainability.

2. Taxonomy assists the team of manufacturing process developers in defining objectives for each of the S^3 solutions. Therefore, technology adoption can be carried out according to the selected level, thereby minimizing the cost, and the selection of solutions is in accordance with the organizational objectives.

3. The S^3 Process Development Reference Framework provides a structure for developing manufacturing processes with S^3 solutions, it delimits the specific

engineering activities at each stage of development. Thus, it provides a guide to the development teams of manufacturing firms that can be instantiated according to their particular needs and with tools from their sector.

4. The proposed Toolbox collects valuable tools for the industrial manufacturing sector. To use it in other sectors, it is necessary to define the tools, norms and standards that apply; however, its consistency has been demonstrated in the case studies. The toolbox provides tools that assist in developing the manufacturing process in conjunction with the defined activities of the S^3 Process Development Reference Framework.

5. The S^3 Scorecard is a proposed evaluation tool that helps characterize the S3 attributes and evaluate the resulting levels of the implementation of S^3 solutions of a manufacturing process. In addition, it serves to give feedback and recommendations for specific technology adoption in S^3 manufacturing processes.

6. The methodology summarizes the contributions generated during this work and guides the development of S^3 manufacturing processes. Its effectiveness has been proven in at least three applications, design, redesign and selection of solutions in manufacturing processes. Thus, it presents defined stages for its implementation in various industrial contexts to develop S^3 manufacturing processes.

The main contribution of this work lies in the structure of thought when addressing manufacturing process design problems. The main problem of the industrial sector was to adopt technological solutions that did not generate value within the organization. This generated a subsequent rejection that was healed from the demonstration of projects in conjunction with the academy. The use of resources allowed the acceptance again and with it the multidimensionality of the different solutions offered. Throughout the development of this work, it was observed that S^3 solutions provide answers to the industrial sector, both productive and aligned to the objectives they pursue. In this way, value generation is perceived, both for the organization and its target audience. Thus, this methodology becomes an enabler in the transition process between traditional manufacturing systems and knowledge-based promoted by I4.0.

7.2 Future work

Due to the deepening of the manufacturing processes, the concept of Sensing, Smart and Sustainable, the study of new technological tools and the implementation of industrial projects, the author's vision of this work had aspects focused on education, industrial processes, human-based designs, and abstraction of concepts to structure ideas.

Sequentially, this work could continue along the side of not only manufacturing but also **i)** organizational processes. Part of this vision has been explored in the first chapters of the dissertation; however, future work would consist of deepening what characterizes this type of process, the interaction with the different entities that make up the organization and finally, the proposal of a methodology for characterizing organizational processes and provide them with characteristics that facilitate their automation.

The taxonomy was created in order to have design objectives for manufacturing processes. One of the main objectives is to strengthen its design in order to increase the value for the manufacturing process development teams. Therefore, one of the future work is to increase its robustness. In working with the industry, a need arose that had not been detailed during the initial design of the taxonomy, **ii)** the inclusion of heat and noise as emissions. Therefore, future work would be centered on increasing the robustness of the taxonomy by including these dimensions as part of the emissions, both in Sensing and Sustainable Solutions.

Another aspect of future work consists of increasing the attributes of the entities, that is, introducing new points of view that allow not only to measure Sensing or Smartness solutions, but as happened with Sustainable, to have objectives that transcend the creation of products, manufacturing processes or systems, but can be perceived by different actors. Currently, **iii)** the inclusion of the Social aspect as a characteristic of analysis of manufacturing entities is under development. This type of concept places the human being as the central axis in design. This type of design generates entities of the S^4 system type; however, the deep definition of the levels that allow its acceptance is still under development.

In addition, this type of definition brought interaction with collaborative networks and **iv)** the design from the perspective of a set that places the Citizen as an entity that interacts with its

Community and, in turn, with the City (C3). This development allows the integral generation of solutions that are not based on the human being but as part of their environment where value can be perceived and combines the use of tools with diverse technological applications.

Derived from the interaction with the industry and simulation systems, other future work consists of **v)** developing a methodology to carry out simulation projects efficiently and iteratively, defining specific action stages and deliverables throughout the creation process. Part of this analysis was designed; however, its deep research and abstraction of engineering activities and tollgates are still required.

Finally, in the industrial domain, together with the abstraction of concepts, the use of visualization techniques, digital representation and decision-making technologies, the automation pyramid was studied and the possibility of developing a digital twin that attends the higher stages for **vi)** automatic decision-making. The bases can be reviewed in the author's publications; however, the experimentation and implementation of the concepts remained as future work, given the separation of the central axis of this work.

The work developed throughout this development has brought with it more questions not only in the manufacturing processes but also in the multiple applications of the knowledge acquired during the journey together with an enriched and structured vision to follow up on the numerous projects and publications explored.

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Research publications

2018 PRO-VE (Conference)

A Framework to Support Industry 4.0: Chemical Company Case Study

Daniel Cortés Serrano[1], Dante Chavarría-Barrientos[1], Arturo Ortega[2], Belén Falcón[2], Leopoldo Mitre[2], Rodrigo Correa[2], Jaime Moreno[2], Rafael Funes[2], Arturo Molina Gutiérrez[1]

[1] Product Innovation Research Group, Tecnologico de Monterrey, School of Engineering and Science, Mexico
{a01655708, dante.chavarria, armolina}@itesm.mx
[2] LOVIS, Mexico
{arturo.ortega, belen.falcon, leopoldo.mitre, rodrigo.correa, jaime.moreno, rafael.funes}@lovis.email

Abstract. The concept of Industry 4.0 corresponds to a new way of organizing the production of goods, taking smarter decisions based on environmental variables and optimizing available resources. However, there is still a journey to carry out the implementation of this concept with current technologies. To make this transformation of the industry, it is necessary to characterize the Industry 4.0 concept, adopt a strategic thinking, and acquire skills, aptitudes, and attitudes. Enterprise reference models can help in orchestrating the change, however, the relationship between existing reference models and Industry 4.0 needs further clarification. Thus, this paper proposes a framework that links a reference model with the Industry 4.0 concept. Furthermore, a tool for the instantiation of the framework is proposed to provide practical approach. And the results of implementing the proposed framework are presented in a case study.

Keywords: Industry 4.0, Cyber-Physical Systems, Industrial Internet of Things, Enterprise Operating System, Cognitive Systems.

1 Introduction

Today, enterprises need to be designed according to customer requirements, optimize available resources, become agile and respond to market changes in intelligent manners [1]. Enterprises are immersed in their context and operation. Monitoring continues changes over environmental variables are expected to adopt new strategies. To make smarter decisions it is necessary to create Collaborative Networks of Cognitive Systems which could exploit new technologies such as Big Data, Industrial Internet of Things, Advanced Robotics, Artificial Intelligence, Hyperconnectivity, Cloud Computing, Cybersecurity, Additive Manufacturing and Cyber-Physical Systems [2]. With the application of this technologies, an enhance their reactive and proactive capabilities are expected [3][4]. Sensing technology is now a reality and

2018 PRO-VE (Conference)

Open Innovation Laboratory for Rapid Realisation of Sensing, Smart and Sustainable Products: Motives, Concepts and Uses in Higher Education

Arturo Molina Gutiérrez[1](✉), Jhonattan Miranda[1], Dante Chavarría[1], Julieta Noguez[1], Miguel Ramírez[1], Manuel E. Macías[1], Edgar O. López[1], Martín R. Bustamante[1], Martín Molina[1], Pedro Ponce[1], Daniel Cortés Serrano[1], and José Ramírez[2]

[1] School of Engineering and Sciences, Tecnológico de Monterrey, Monterrey, Mexico
{armolina, jhonattan.miranda, dante.chavarria, jnoguez, miguel.ramirez, mmacias, edlopez, rbustama, jose.molina, pedro.ponce, a01655708}@itesm.mx
[2] Instituto Tecnologico de Tlahuac, Mexico City, Mexico
pep_antonio@hotmail.com

Abstract. Open Innovation is not a new concept and it is been actively used by different entities to cope with new challenges posed by the evolving society in business, science and education. However, for this last one seems to be poor documentation about how higher education institutions are dealing with it. It is evident that universities are applying concepts like Open Innovation Laboratories, however it is not clear the methodologies or resources they are using. Tecnologico de Monterrey recently created its own laboratory and in this article we present the motives, concepts and uses of it in the context of higher education. Different approaches are made, from the development of core competences concepts to the physical and virtual tools used in the lab. Two study cases are briefly presented in order to illuminate how external actors are collaborating with internal actors in an Open Innovation process.

Keywords: Open Innovation · Open Innovation Lab
New product development · Sensing smart and sustainable products
Collaborative Networks · Higher education

1 Introduction

The globalized world in which we live is getting increasingly competitive and there is the need to solve fast and in a novelty way the challenges that arise in business, science and education [1]. Evolution of Communication and Information Technologies (ICTs) broke geographic barriers and allowed the expansion of Collaborative Networks (CN) and the transformation of Open Innovation (OI). The OI assumes that innovation process is an action where not only internal actors within an institution or and enterprise participate

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Integrated Product, Process and Manufacturing System Development

3D Food Printer as Case Study

Cortés, Daniel; Rodríguez, Blanca E.; Gutiérrez, Janet A.; Welti, Jorge; Serna, Sergio; Molina, Arturo
Tecnologico de Monterrey
School of Engineering and Sciences
Mexico City

Montoya, Juliana; Medina, Jorge
Universidad de los Andes
School of Engineering
Colombia

***Abstract*—This paper is referred to the application of Integrated Product, Process and Manufacturing System - Reference Mode (IPPMD-RM) to develop a functional machine which contributes binational problems (Colombia-Mexico) in terms of Food Security supported by the application of technology. Thus, activities are proposed, from idea conceptualization to prototype development. IPPMD-RM contemplates 4 different stages in 3 entities and every step is analyzed, synthesize and evaluated to confirm its functionality and acceptance of customer. 3D Food Printer is the application of the Reference Model to existing necessities in both countries.**

***Keywords*—Extrusion; 3D food printer; emergent technology; manufacturing enterprise; innovation.**

I. Introduction

Manufacturing processes need to respond faster, provide valuable information and be designed considering at least 3 entities: (1) society, (2) enterprise and (3) environment. With these three challenges to overcome, manufacturing processes are expected to be intelligent [1] vanishing boundaries between real and virtual world. On the other hand, Smart, Sensing and Sustainable (S^3) manufacturing approach [2] aids enterprises monitoring their context and operations; their decisions are taken not only with own information but with their environment and supported by different technologies to accomplish smarter decisions. Today, enterprises face worldwide competence and the ability to create competitiveness advantage [3] is needed to occupy a position in market, creating Collaborative Networks [4] enhance reactive and proactive capabilities among enterprises and generates competence in digital era. To be connected to customer provides valuable information to react in agile and precise manners [5], Integrated Product Process and Manufacturing System Development Reference Model (IPPMD-RM) [6] and S^3 approach provides continuous information to respond digital era challenges. Smart, understood as the ability of enterprises to communicate and generate interconnectivity between their processes, capable to process information and take advantage of opportunities analyzed in real time [7]. Sensing, referring to methods enterprises adapt to be aware of the environment [5] and provide responses to future events. Sustainable, measured as the positive impact of an enterprise in three different areas: (1) social, understood as the needs of community and how to provide a long-term solution to them, (2) economic, referent to the positive impact among resources of the company that creates value and, (3) environmental, as the capability of an enterprise to reduce impact and contributes to preserve nature [8]. S^3 enterprise are becoming a reality due to the convergence of different technologies and applications of them in different areas. More industries are adopting and migrating their traditional methodologies and skills to gather information, with this, acquiring technology and adopting information strategies to provide real time data, have become an advantage that allows enterprises knowledge-based decision making [9]. Manufacturing industry is undergoing challenges due to global competence [10], demographic and cultural factors, but above all else, technology has become a key factor that is reflected in products, services and effective processes. Thus, technological innovation, CPPS and intangible actives inside enterprises [11] are the advantages digital era requires. To become part of digital era, S^3 enterprises should integrate CPPS into productions sites, process information in real-time of market movements and be capable to give response to market demands [12]. However, a more intelligent, interconnected and autonomous vision is expected, to analyze information. It is intended that the manufacturing industry faces the creation of specialized products with short production times which implies changes in the way of conceiving products and systems in general. The demand for this type of change brings with it modifications that allow to be highly flexible and adaptable to compete in a globalized world. Thus, mass production becomes economically less viable and it seeks to introduce adaptation to market demands by becoming more customizable and covering the existing needs of the population. What technological changes seek in this context is in itself, the connection of manufacturing systems, the connection with the different stages of the production process and finally, adapt to customer needs in a very efficient manner. With these 3 connections, the benefit that is expected is the maximum value creation without neglecting the value chain, through the continuous flow of information and continuous improvement of the process [13] S^3 enterprises demand higher skills and qualifications, working with continuous information and determining the value of it,

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Experiences in Product, Process and Manufacturing Systems Development in Industrial Engineering Courses:

The Integrated Manufacturing System course as case study

Dante Chavarría-Barrientos, Jhonattan Miranda, Daniel Cortés, Arturo Molina
Tecnologico de Monterrey,
School of Engineering and Science,
Mexico City, ZIP 14380

Abstract—This paper presents the methodological use of the Integrated Product, Process and Manufacturing System Development (IPPMD) as Reference Model to reinforce the learning experience in industrial engineering courses. The Reference Model allows students to design and develop a product, its manufacturing process, and its manufacturing system in an integrated manner using modern technologies and methods. The incorporation of this Reference Model on the curriculum is embraced by modern learning methods and collaborative and technological tools that allow students to improve their learning process. A case study is shown to demonstrate the way in which this reference model is used. The results presented show the usefulness of the proposed reference model in an Integrated Manufacturing System course.

Keywords— Collaborative Learning; Active Learning; Industrial Engineering; Integrated Product Development; Manufacturing Systems Development.

1. Introduction

Today, students are learning in diverse ways. Thus, they are taking advantage of technologies such as the Internet, and new Information and Communication Technologies (ICT). Therefore, learning methods have evolved to provide the necessary tools to face real problems. Students can develop the necessary skills to propose solutions to social problems of today's society. The digital age in education has a key role during this learning process. Therefore, scholars and researchers have been developing new learning methods incorporating ICTs and advanced devices. These technologies allow students to have different learning experiences, so they can simulate real scenarios to analyse processes which enable them to stimulate their analysis and observation capacities, to develop technical skills, and to get experiences in the making decision processes. In this sense, Tecnologico de Monterrey, Mexico is developing new learning methods and collaborative tools that involucrate these new technologies. The main idea is to provide new learning environments and learning communities to improve the learning process.

The Integrated Product, Process and Manufacturing System Development (IPPMD) reference model is an approach that allows students to develop in an integrated way not only new products, but also their manufacturing processes, their manufacturing system and enterprise strategies. This reference model provides a set of tools and methods to design and develop these different entities. Furthermore, the reference model improves the learning experience by promoting techniques such as collaborative and active learning.

This paper aims at demonstrating the use of the IPPMD Reference Model and its associated tools as a novel technic for implementing active and collaborative learning in industrial engineering courses. Section 2 presents a review of these learning technics and its applications. Then, Section 3 presents the reference model and the primary tools used during each of the stages. After that, Section 4 presents a case study to demonstrate the implementation of the reference models and tools. Finally, the evaluation of the proposed framework is performed using a reference framework for learning innovation.

2. Collaborative and active learning

Collaborative and active learning allows the students to enhance their learning experience. Following subsections explain how these concepts have revolutionized the student's understanding.

2.1 Collaborative Learning

The collaborative learning is a technique in which people come together in groups to cooperate; the individual abilities are highlighted to create an environment in which knowledge is constructed, discovered and transformed by students [1]. The principles of this technique are: the understanding overcomes what would occur if members had worked independently; interactions contribute to this increasing understanding; participation is voluntary. In contrast with the cooperative learning where the teacher is not in total control of the learning environment and the labour is divided and assigned to members, collaborative learning involves engagement of participants to solve a problem [2]. Therefore the students can receive large amounts of information which help them in the production of ideas to complete their learning tasks. Researchers have concluded that this type of technique can be enriched with the use of technological tools such as computer games [3]. Furthermore, the learning outcomes when including technology in collaborative learning were significantly better than conventional approaches [4].

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Integrated Product, Process and Manufacturing System Development Reference Model: Research Summer as case study

Daniel Cortés, PhD student[1], José Ramírez, Mechatronics student[2], Dante Chavarría-Barrientos, PhD, Jhonattan Miranda, PhD and Arturo Molina, PhD[1]
[1]Tecnológico de Monterrey, Mexico City, a01655708@itesm.mx, armolina@itesm.mx
[2]Instituto Tecnológico de Tláhuac, Mexico City, pep_antonio@hotmail.com

Abstract*– Open Innovation Laboratory has been developed as an integrated solution that gather all productive stages lifecycle, from ideation to promotion of products. However, every stage of product lifecycle is considered in Integrated Product, Process and Manufacturing System Development (IPPMD) it has been used as Reference Model as approach to reinforce education at higher studies. This Reference Model allows students designing from conceptual ideas to functional prototypes: Products, its manufacturing Process and its Manufacturing System. IPPMD Reference Model (IPPMD-RF) has been integrated in courses of industrial engineering to improve learning process and consolidate previous knowledge related with major. In recent years, this methodology has been extended to Massive Open On-line Courses (MOOCs) and it also has been applied as a technique for those students who forms part of research summer. A case study is shown to demonstrate how this IPPMD as Reference Model works. The results obtained with this Reference Model has proven its usefulness and participants have consolidated multiple area knowledge in different projects.

Keywords—Industrial Engineering, Integrated Product, Process and Manufacturing System, Collaborative Learning.

I. Introduction

Nowadays, students are taking advantage of different technologies such as Internet of Things (IoT) and new Information and Communication Technologies (ICT). Consequently, students have become more agile and proactive on their studies and professors acquire the role of information facilitators and leaders of knowledge. In this context, students become more interested in thinking and generating ideas than just following instructions as in standard techniques of education. Technologies are now part of the environment for everybody and students are not exempted. Even these technologies and resources are available, not everybody has access to them and those who do take part on the proposes to provide social, economic and sustainable solutions. ICT and IoT resources can be used to improve and complement traditional education, their main goal is to exchange information and material among classmates and instructors. Thus, scholars and researchers have been developing new learning techniques and methodologies to improve education. In order to integrate multidisciplinary knowledge, improve analytical and critical skills, develop capabilities of observation and decision-making process, forecast different scenarios and get experience in different subjects of their major, Monterrey Institute of Technology and Higher Education, Mexico is developing new spaces provided with tools and technology to foment collaborative learning.

The Integrated Product, Process and Manufacturing System Development Reference Model (IPPMD-RM) is an approach that allows students to decompose product lifecycle into product, process and manufacturing system, however, students are not only encouraged to learn this methodology, but complement it with different approaches in order to elaborate products that respond to economic, social and sustainable problems. IPPMD-RM provides a set of tools to design and develop according to three different entities in four different stages. Thus, learners improve experience and develop different technical and social skills.

This paper aims at demonstrating the use of IPPMD-RM and its set of tools as a technique for implementing active learning in Research summer (students who aim to collaborate in Research projects during summer). At Monterrey Institute of Technology and Higher Education, Mexico this IPPMD-RM has been implemented in Integrated Manufacturing Systems course, there is also a MOOC providing this technique to everybody interested in learning it and Research summer was an opportunity to test this technique with multidisciplinary teams.

Section 2 introduces a review of learning techniques. Afterwards, Section 3 presents the Reference Model, entities, stages and tools applied during each stage. Purpose, Section 4 presents a case study to demonstrate the implementation phase of the IPPMD-RM and tools. Thereupon, conclusions are presented according to Research summer experience.

II. Learning Techniques

Active and Collaborative Learning allows multidisciplinary teams to improve their projects and in general, their ideas while developing functional products according to different viewpoints. With the IoT and ICT education have acquired a potential tool to exploit, collaboration [1][2]. Nowadays, students are able to complement ideas and reinforce concepts while collaborating in real time with their classmates.

II.1 Active Learning

Active Learning (AL) aims at the enrichment of traditional techniques. Students are encouraged to engage with subject, this contrast with traditional methods where lecturers

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Sensing, smart and sustainable products to support health and well-being in communities

Jhonattan Miranda, Daniel Cortés, Pedro Ponce, Julieta Noguez, José Martín Molina E., Edgar O. López, Arturo Molina
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
jhonattan.miranda@tec.mx, a01655708@tec.mx, pedro.ponce@tec.mx, jnoguez@tec.mx, jose.molina@tec.mx edlopez@tec.mx, armolina@tec.mx

***Abstract*—Today, the healthcare industry has been highly influenced by the "Industry 4.0" concept and vision. Therefore, the healthcare industry is taking advantage of new technologies, information and communication technologies (ICTs), the internet of things (IoT), innovative practices and procedures to provide better products/services, process and facilities. In this work, the "sensing, smart and sustainable (S^3)" concept is used to design and develop new technologies that promote well-being and ensure health in communities.**

Keywords—Healthcare 4.0, Health and Well-Being, Sustainable Development Goals, Smart Products, Sustainable Products

I. INTRODUCTION

Human health is one of the most important development objectives that countries consider a priority on their agenda. In this sense, the manufacturing sector has an important role, since, through the healthcare industry, it is responsible for providing new products/services to treat patients with curative, preventive, rehabilitation and palliative care [1].

According to the World Health Organization (WHO), the health industry has contributed to a significant percentage of the world's Gross Domestic Product (GDP). In the USA, the healthcare industry contributes about 17.9% of GDP, the largest of all the countries in the world [2]. Consequently, with these data, we can figure out the economic relevance and social importance of providing new technologies, and in this way, find the best mechanisms to face the current challenges that exist in this sector and society.

In this sense, the healthcare industry has been influenced by the concept and vision of the "Industry 4.0", taking advantage of emergent technologies such as process automation, digitalisation, emerging information and communication technologies (ICTs) which have been powered by the Internet of Things (IoT); hence, cyber-physical systems (CPS) and smart connected products have been obtained [3]. These technologies have given way to a new era of the healthcare industry that in recent times has been known as the "Healthcare 4.0" [4].

In this context, the concept "sensing, smart and sustainable (S^3)" emerged to provide new technologies that can meet current social challenges [5]. The "sensing concept" refers to the capability of a product to detect events, acquire data, and measure changes that occur in an environment. The "smart concept" refers to the capability of a product to incorporate actuation and control functions to describe and analyse situations and make decisions based on the available data in a predictive or adaptive manner. Moreover, the "sustainable concept" is used to provide sustainable products/services considering social, economic and environmental design objectives. Hence, applying these concepts in a new product development process, we can provide high technology solutions with sustainable value.

In this work, the authors present a brief description of the current panorama in the health and well-being sector to provide an approach to current topics, research lines, and opportunities areas. Also, this work presents how a reference framework for the development of sensing, smart and sustainable (S^3) products is used to create technologies for the health and well-being sector. Finally, four examples of S^3 products are presented to illustrate the given context.

II. TECHNOLOGIES FOR GOOD HEALTH AND WELL-BEING

Efforts to support good health and well-being initiatives have gained considerable importance in recent years due to the significant social, economic and environmental impacts that affect the global society [6]. In 2015, the United Nations General Assembly (UNGA) established the global goals for sustainable development, which defined 17 Sustainable Development Goals (SDG) that cover issues of social and economic growth [7]. In this context, attention to health and well-being issues were considered as one of the priority goals. Consequently, this goal promotes the realisation of initiatives that provide good health and improve well-being in communities.

According to the WHO, health is defined "as a state of complete physical, mental and social well-being of individual and not the mere absence of diseases or infirmities" [8]. In a technology context, the health has been highly benefited by several technologies, which are related to providing new medicines and treatments, new medical tools and equipment, innovative medical procedures, services and facilities, among others [9]. Also, health is essential for the well-being of society, since a good state of health allows individuals to access practically the full range of human functions. Well-being is a human condition where psychological, emotional and social aspects affect the feelings related to being comfortable, healthy or happy [10]. Table I presents an approach to current topics, research lines and opportunity areas in the healthcare industry [6].

TABLE I. THE APPROACH TO CURRENT TOPICS, RESEARCH LINES AND OPPORTUNITIES AREAS IN THE HEALTHCARE INDUSTRY

Topics	Topics, research lines and opportunities areas
Medical equipment and tools	▪ 4.0 context (e.g. prosthesis, surgery, orthopaedics) ▪ Robot-based training ▪ Measurement and monitoring tools (e.g. glucose monitoring, cardiac monitoring, health tracker, blood pressure monitoring, ingestible pill sensors) ▪ Robotics (e.g. robotic surgery, teleoperated service robots, nanorobotics, therapeutic robots, assistant robots) ▪ Digital imaging processing ▪ Wearable systems ▪ Micro wireless physiological sensors

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Discrete Event Simulation as a Support in the Decision Making to Improve Product and Process in the Automotive Industry - A Fuel Pump Component Case Study

Luis E. Villagomez[1(✉)], Daniel Cortés[1], José Ramírez[1], Alejandro Álvarez[1], Rafael Batres[1], Ivann Reyes[2], Germán Esparza[3], Nancy Cruz[3], and Arturo Molina[1]

[1] School of Engineering and Sciences, Tecnologico de Monterrey, 14380 Mexico City, Mexico
{levg, a01655708, a00995924, a01421567, rafael.batres, armolina}@tec.mx
[2] Grupo Dinamex, S.A. Technical Support, Mexico, 52976 Lopez Mateos, Mexico
ireyes@dinamex.com.mx
[3] Siemens PLM Mesoamerica, Mexico City, Mexico
{german.esparza, nancy.cruz}@siemens.com

Abstract. In Mexico, the automotive sector is one of the most profitable industrial activities as it contributes 2.9% of the national GDP [1]. However, there still exist facilities that are in transit of manufacturing processes improvement. In recent years, the adoption of emergent technologies, practices and tools that lead into the Industry 4.0, has been a parameter to compete and remain competitive in the global market. Upgrading all the processes is not always a viable solution. Thus, companies must identify the optimal solution to increase their productivity. Numerous technologies are available to facilitate this migration. This paper aims to show how discrete event simulation with an action research cycle supports the decision making in process improvement aided by the information collected in Collaborative Networks. A case study is shown in the automotive sector to validate changes in processes based on estimated energy consumption, maintenance strategies, process time reduction and the implementation of state-of-the-art sustainable processes.

Keywords: Automotive industry · Discrete event simulation · Plant Simulation · Plasma nitriding · Modeling and simulation · Collaborative Networks

1 Introduction

In recent years, Industry 4.0 has been a parameter of progress among the developing countries [2–4]. The adoption of new information technologies and techniques can promote sustainable motives [5] within a circular economy [6], with an integral society [7] and environmental benefits [8, 9]. According to Stock and Seliger [10], sustainability

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3D Virtual Environments to Support New Product Development: A Mobile Platform based on an Open Innovation Laboratory applied in Higher Education

José Martín Molina[1], Jhonattan Miranda[1], Daniel Cortés[1], Jorge Medina[2] and Arturo Molina[1]

[1]School of Engineering and Sciences
Tecnologico de Monterrey, Mexico City Campus, Mexico
jose.molina@tec.mx, jhonattan.miranda@tec.mx, a01655708@tec.mx, armolina@tec.mx
[2]Mechanical Engineering Department
Universidad de Los Andes, Bogotá, Colombia
jmedina@uniandes.edu.co

Abstract. Nowadays, it is observed that native digital students demand the use of innovative learning methods, as well as the use of specialized technological equipment that can positively influence their professional training, but at the same time it is observed that there is still a deficit not only in the commitment and interest of students to learn, but also to relate how they can apply the knowledge obtained by proposing solutions to real problems. This paper proposes a mobile platform based on 3D virtual environments to support new product development (NPD) as an alternative to address these issues in the Higher Education sector. This mobile platform is an interactive and learning management system that is used to efficiently gather and manage the tangible/intangible resources necessary in an Open Innovation process for the development of new products in which the co-creation and co-development take place. Therefore, an Open Innovation Laboratory applied in higher education was used as a reference. A case study is presented to demonstrate how the proposed platform can be applied in the higher education context.

Keywords: Multimedia and Education; Multimedia Interfaces; Virtual and Augmented Reality; Educational Innovation, Higher Education.

1 Introduction

Today, there are still challenges in the higher education sector to improve teaching-learning processes that are mainly related to the deficit in the motivation and interest of students to learn including intrinsic and extrinsic motivations, the link between the acquired knowledge and the labor work, the difficulty in developing desirable competencies in today's student profile, among others [1], [2]. In recent years, there are emerging initiatives related with the concept and vision of Education 4.0 to face these challenges

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A model for plant digitalisation, simulation and improvement: A case study in the automotive tier one supplier

Daniel Cortés*, José Ramírez, Luis E. Villagómez, Rafael Batres, Arturo Molina
Escuela de Ingeniería y Ciencias
Tecnologico de Monterrey,
Mexico City, Mexico
*e-mail address:
a01655708@itesm.mx,
a00995924@itesm.mx,
levg@itesm.mx, rafael.batres@tec.mx,
amolina@tec.mx

Ailin Velilla**, Gerardo Lozano, Emilio González, Jaime Puente
BOCAR Group
State of Mexico, Mexico
**e-mail:
address:ailin.velilla@bocar.com,
gerardo.lozano@bocar.com,
emilio.gonzalez@bocar.com,
jaime.puente@bocar.com

Germán Esparza***, Nancy Cruz
SIEMENS PLM Mesoamerica
Mexico City, Mexico
***e-mail address:
german.esparza_sedas@siemens.com,
nancy.cruz@siemens.com

***Abstract*— Digital manufacturing has been proved as an enabler of process planning and decision making in industry, showing improved results with the adoption of this technique. Taking advantage of the interconnectivity offered by Industry 4.0 technologies, it is possible to analyse the entire process as individual entities with their characteristics. Besides, simulation creates a digital environment which relies on information to reflect the reality of manufacturing plants, the primary motivation of simulation investment is the creation of different scenarios targeting business' mission. The model presented in this article gathers information from different entities aided by Sensing, Smart and Sustainable (S3) characteristics in order to digitalise a manufacturing plant and improve the decision- making process. It targets the whole manufacturing process as an opportunity to improve practices among the enterprise business model, taking into account the infrastructure of the operations, workers and the flow of information and material. In one hand, Sensing and Smart attributes are embedded in new machines and technology to enable interconnectivity, on the other hand, Sustainability is achieved in the process by the joint effort of the executive council of the organisation.**

Keywords—Advanced Manufacturing; Digital Manufacturing; Discrete Event Simulation; Offline Programming; Virtual Ergonomics; Decision Making; Automotive Industry.

I. Introduction

In recent years, manufacturing has experienced fast-paced changes aligned with Industry 4.0 continuous evolution. As stated by Josvai et al. [1] this evolution is based on three main science fields: Computer Science (CS), Information and Communication Technologies (ICT) and Manufacturing Science Technologies (MST). The resulting synergy of the aforementioned evolves continuously to provide reliable solutions to the modern industry [2]; however, key characteristics are necessary to provide valuable informationto commit improvement. Although current manufacturing era uses complex technologies, tools and practices, as a rule, Industry 4.0 is built on the fact that its systems tend to acquire data by different sensing technologies. Also, the integration of all the resources benefit directly from the information flow among humans and machines (digital and physical), thanks to the advantage of different decision-making approaches hence a smart component is present [3]. Besides, there is an ongoing effort to take advantage of modern technologies in terms of reaching higher levels of productivity [4] with a positive impact on economics, society and the environment, the three aspects of the sustainable index.

Current manufacturing practices rely heavily on computing power thus the term Digital Manufacturing (DM) which comprises electronic and computer-based systems, rapid prototyping techniques, control systems, product customisation, cybersecurity, among others [5][6]. Digital Simulation as part of the DM stands out as it takes advantage of forecasting a precise result when certain variables are processed in specialised software enabling what is known as Manufacturing System Simulation (MSS). The relies on three main fields (See Fig. 1): Virtual ergonomics, Virtual commissioning and Discrete Event Simulation (DES). Each one of them contributes to different aspects of the business model.

Fig. 1. *MSS three main branches.*

Virtual ergonomics is centred on the well-being of the workforce, covering social agenda besides sustainable motives. Virtual commissioning targets the optimal functions of cyber-physical systems. DES aims at resource consumption, logistics and distribution among daily operations. Thus, MSS takes advantage of the facility

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Analysis of Productivity and Profitability of a SME through Collaborative Networks using Discrete Event Simulation tool: An automotive Case Study

Emigdio Martínez[1], Daniel Cortés[2], José Ramírez[2], María Guadalupe Obregón[1] and Arturo Molina[2]

[1] Instituto Politécnico Nacional, UPIICSA, 08400 Mexico City, Mexico
emigdiomartinez22@gmail.com, nathauo@hotmail.com
[2] School of Engineering and Sciences, Tecnologico de Monterrey, 14380 Mexico City, Mexico
{ a01655708, a00995924}@itesm.mx, armolina@tec.mx

Abstract. Most companies seek sustainability and competitive advantage for optimal problem solving and value creation. Medium-sized companies that account for more than 90% of the world's total companies with a low research & development, tend to search for alternatives within the private and educational sector that allow them to increase their productivity without having to compromise their competitive activity in their sector. Collaboration with external actors represents an opportunity for organizations as it broadens their development of the productive system and their organizational behaviour. This interaction is known as Open Innovation. This concept has dismantled the traditional organizational archetype enabling universities to link the academy's work into the industrial sector. One-part of the academy, in collaboration with them, is the use of emerging technologies and digital tools that lead into a decision-making efficient process incorporating industry 4.0. A useful technology for this purpose is Discrete Event Simulation, a tool for system analysis, characterized by modifying variables without compromising the current productivity of the company. This document explains through a case study, the use of simulation in an enterprise of the automotive sector through the tool, in the lamination process of production line. The contribution of this paper is generating alternatives for the decision-making process in a real scenario, using the tool to achieve results in collaboration within the industry sector. The analysis shows the improvement, analyzing the productivity and choices, that increase in the profitability of the enterprise.

Keywords: Discrete Event Simulation, Industry 4.0, Value Creation, Collaborative Networks, Making-decision, SME, Automotive industry.

1 Introduction

Nowadays, Industry 4.0 plays an important role in competitive advantage for many enterprises. All the phases of the industrial revolutions have led great changes to

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Open Innovation Laboratory: Education 4.0 Environments to improve competencies in scholars

Daniel Cortes[1], MSc, Jose Ramirez[1], Eng and Arturo Molina[1], PhD
[1]Tecnologico de Monterrey, Mexico City {a016655708,a00995924}@itesm.mx, armolina@tec.mx

Abstract*– With the widespread adoption of emergent technologies, productive sectors have evolved in leaps and bounds This has generated a breach between what is needed in the Industry and what is expected in Academia to be taught. Traditional education focuses on the development of hard skills in students, nonetheless, current technology developments mainly in the fields of artificial intelligence and automation pose a threat to technique and repetitive jobs. Soft skills on the other hand are to remain active and desired in the near future as they are needed for tasks that machines cannot replicate yet. Complex problems require the integration of multidisciplinary teams where decision-making and communication abilities are enhanced by its individual parts. Mass adoption of Information and Communication Technologies in every sector of society demands an evolution of the education model. Consequently, universities throughout lecturers and infrastructure must develop guidelines for students to improve their skills and generate the competences needed. The open innovation concept has brought institutions a framework to develop multidisciplinary and multi entity projects to provide valuable experiences and competencies development to college students. This has led to the development of Open Innovation Laboratories where learning techniques, design methodologies and product realisation platforms fuse to provide a state-of-the-art concept to cope with the demands toward the educational model. This allows joint efforts from industry, government and institutions on the creation of collaborative projects to provide innovative solutions whilst enriching experience and boosting competences in students. Thus, the idea of gathering emergent technologies for training, open innovation for generating end-to-end solutions and methodologies to foster strengths in students becomes an educational environment to promote the use of active and collaborative learning techniques to enhance soft skills and development of competences facing society challenges as part of the education 4.0 context.

Keywords*– Collaborative and Active Learning, Education 4.0, Educational Innovation, Higher Education, Integrated Product, Process and Manufacturing System Development, Learning Environments, Open Innovation Laboratory.

I. Introduction

Social, economic and environmental changes driven by information technologies are defining today's society. Productive sectors (primary, secondary and tertiary) are in constant evolution and there are at least two new sectors that must be included into this classification [1]. This increasing complexity exhibits the evolution of all social structure. For instance, the primary sector is under high pressure to find new practices in order to preserve and protect these non-renewable resources. New regulations seem to conflict with the increased needs of population growth entailing a rational speed up of exploitation. Even new trends in human feed patterns [2], including the demand of organic food represent a challenge to this sector requiring new responsible ways of production. On the other hand, the industrial sector is the maximum representative of the innovation that is being carried out thanks to the constant evolution of technology. Both extraction and transformation are experiencing deep changes easily observable as their flagship corporations lead the transformation into Industry 4.0 [3]. For the service sector, there is ongoing work to make the most of new production models and technologies. Widespread use of the internet has enabled the creation of new business models, growth of e-commerce and transformation of services thanks to fog and cloud computing [4]. To this extent, all sectors are constantly evolving and require professionals able to deal with current and future problems by means of specific skills and competences to propose innovative solutions that break the paradigm of the traditional way of doing things.

Formation of new generations must be in accordance with new educational techniques allowing professionals to face current and forthcoming challenges [5]. Much of this instruction is still carried out in conventional spaces even on the most prestigious institutions. Although there has been a constant evolution in different sectors of society, educational methods and learning techniques remain roughly the same as a century ago. Grads finishing their formation will encounter a demanding environment whether they want to enter the workforce of a company or, on the contrary, adventure themselves into the world of entrepreneurship. For universities around the world there is a continuing effort to improve their curricula to allow the development of the most demanded skills in students [6]. This step forward in learning culture is becoming known as Education 4.0 (Ed 4.0).

The purpose of this article is to show how disciplinary and transversal skills in scholars are improved through Ed 4.0 environments, such as Open Innovation Laboratories. A space which brings together industry and academia collaborations to share experiences about challenging engineering projects, promoting an integral development for students. To address these challenges of the productive sectors, students make use of technologies, methodologies and tools. The present paper is structured as follows. In Section II, there is divulged the conception of Ed 4.0 observing the advances of technology and their impact on future professionals. Then, in Section III, there are described the Open Innovation Laboratories (OIL) and current efforts of Universities to develop competences in students through them. Soon after, in Section IV, the educational environment to foster competences in the context of Ed 4.0 using OILs is exposed. Thereupon, in Section V, there are uncovered three case studies developed in the educational environment at Tecnologico de Monterrey.

II. Education 4.0 concepts and trends

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Digital Pyramid: an approach to relate industrial automation and digital twin concepts

Daniel Cortés
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
a01655708@itesm.mx

José Ramírez
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
a00995924@itesm.mx

Luis Villagómez
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
levg@tec.mx

Rafael Batres
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
rafael.batres@tec.mx

Virgilio Vasquez-Lopez
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
vlopez@tec.mx

Arturo Molina
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
armolina@tec.mx

Abstract— **The so-called fourth industrial revolution has brought different technologies to aid in the launching of new products, automation of manufacturing process and designing of intelligent manufacturing systems to monitor and control activities inside the factories. One recurrent challenge of the industrial sector is to evaluate multiple scenarios to make decisions at different levels of the business model. Innovative technologies and tools are used to provide solutions to existing gaps in current manufacturing systems. The evaluation of scenarios is used to manage risks, costs, prepare for upcoming work and forecast demand. Thus, the use of Digital Twin (DT) has proven its value covering the simulation and creation of virtual environments without the physical investment needed. With emergent technologies comes to a great responsibility for institutes to prepare undergraduate students in the development of novel skills, thus, technologies should be adapted and included into the teaching-learning process to aid the adoption from educational to the industrial sector. In this work, it is shown how the adoption of DT has been used to teach industrial concepts such as the automation pyramid, the programming of programmable logic controllers PLC and the exchange of information through industrial networks along with the concepts that constitute digital twins, such as digital master, digital shadow and modelling through system dynamics. Besides, the general vision of how digitalization is understood aligned to the vision of education 4.0 and applied to teach a tool to reduce the time for decision making into the industrial sector.**

Keywords—Educational Innovation, Higher Education, Industry 4.0, Digital Twin, Virtual Commissioning, Digital Pyramid, Industrial Automation.

I. Introduction

Productive sector challenges and continuous evolution has led to the need for a more qualified workforce that can propose innovative solutions to the ongoing requirements within the manufacturing industry. Then a synergy employing active collaboration and the use of innovative tools is necessary to link the concepts learned during lectures and the practical approach in the industry. From one perspective, there are constant efforts to provide a new educational approach to bring the desired skills and competences to future professionals [1]. The intensive use of digital technologies to enrich the education experience aimed at the development of disciplinary and transversal skills. STEM (Science, Technology, Engineering & Mathematics) disciplines are highly benefited from the inclusion of technologies such as discrete event simulation (DES), digital twin (DT), additive manufacturing, computer-aided design (CAM), management systems, cloud computing, among others. This, in turn, provides the student with the necessary experience and insight to develop novel solutions to the continuous evolving sectors of the society [2].

From another perspective, the manufacturing industry transforms and evolves at a fast pace and improved Information and Communication Technologies (ICT) have allowed this sector to be more efficient at all levels. This has generated a positive impact in different areas such as energy consumption, waste reduction, water pollution and idle times reduction. The increased governments' regulations around the world in conjunction with the evolving market behaviour including shorter life cycles, personalized products, cost reduction, environmental and energetic regulations have driven the industry to update previous manufacturing models and to adopt new technologies to keep the pace of the world needs [3]. All in all, this revolutionary approach has led to what we call Industry 4.0 that relies on numerous tools and enabler technologies to provide foundations to the emerging manufacturing trends.

Automation is an essential part of the manufacturing sector and one that is being greatly studied by some disciplines. To this regard, the automation pyramid is a model that allows the study of the structure within a manufacturing system as it organizes hierarchically automation according to concepts like communication and complexity. While this works well for structure comprehension it can also be benefited with digitization and virtualization tools as they stand as a valuable solution to explore possibilities without risks. As computing power has increased year by year, DTs and novel techniques and algorithms have the power to simulate and forecast complex environments and allow safe experimentation on "what if…?" scenarios[4]. The outcome will resemble more and more to real-life as the model increases its complexity by enriching from more inputs and a better design. For instance, DT offers a whole approach for studying production processes and is widely used for modelling devices on the Operational Technologies (OT) of the shop floor [5].

Automation understanding and learning can be linked through the use of the automation pyramid and DTs to create a completely virtual environment where all components of the physical world have its digital counterpart for better understanding of the manufacturing system at all levels. These virtual systems allow testing different scenarios, production

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Challenges of Education 4.0 A pathway to potentiate competencies in undergraduate students through Discrete Event Simulation

Martínez, Emigdio[1], Cortés, Daniel[2]
[1] Engineering Department, Instituto Tecnologico de Tlahuac III
Tecnologico Nacional de Mexico, 13278, Mexico City, Mexico
emigdiomartinez22@gmail.com
[2] School of Engineering and Sciences, Tecnologico de Monterrey,
14380, Mexico City, Mexico
a01655708@itesm.mx

Abstract. With the growing development of the industry towards the paradigms established by Industry 4.0, challenges of migration, technological selection, operational, maintenance and life cycle have been observed. However, the challenge of most significant concern is the constant updating and training culture. This gradual effort for the industry brings benefits for the countries and society. At least three actors need endeavour: industry, government, and academic institutions. The latter is intended to cover the students' knowledge and the development of competencies. This translates to the industrial sector as the ability to solve problems creatively using technological resources. This communication process, learning not only based on knowledge but exploitation of technological issues, has been called Education 4.0. Hence, this work presents a methodology for adopting Discrete Event Simulation as a complementary course to the traditional learning process. Results show the competencies fostered and the vision given by technological tools adoption.

Keywords: 21st Century Competencies, Challenge-Based Learning, Discrete Event Simulation, Education 4.0, Industry 4.0.

1 Introduction

Organizations express their need to transform their antique organizational archetypes with technologies, digitization and knowledge into structures and systems that dismantled the traditional paradigm. The union of these resources on a large scale has become the objective to be met within the industry, offering a system capable of learning, providing feedback, communicating, and optimizing, but offering tailored solutions to the users of the products. This change has only been possible in a conceptual way, as stated in [1] so that Industry 4.0 (I4.0) has become a revolution pursued by the industry in general terms.

One of the irrevocably necessary participants for these changes has been trained human resources. In other terms, the human talent attraction. This phenomenon has focused on establishing new methodologies, providing tools, and developing skills, especially in

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Open Innovation Laboratory to foster skills and competencies in higher education

Cortés Daniel
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
a01655708@itesm.mx

Ramírez José
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
a00995924@itesm.mx

Molina Arturo
School of Engineering and Sciences
Tecnologico de Monterrey
Mexico City, Mexico
armolina@tec.mx

***Abstract*— Rapid industry evolution at different levels aligns with continuous socioeconomic worldwide transformation. This paradigm shift will urge professionals capable of responding quickly and decisive to the forthcoming challenges. Then, the development of specific skills becomes paramount for higher education institutions. Education 4.0 trends seek to promote the development of competencies with different tools using a holistic approach, embracing projects and real-life problems to enrich learners' experience. Open Innovation provides a collaboration framework for educational institutions, government, and industry to pursue a common goal and agenda. The synergy of previous concepts blends into Open Innovation Laboratories that includes novel learning techniques, design methodologies and realization platforms to provide valuable means for the academy that stimulates student's development of required skills and competencies in this everchanging world. This paper briefly explores the foundations and deployment of such a laboratory at Tecnologico de Monterrey. Three case studies are presented to illustrate different initiatives held during 2019 and 2020 that demonstrate clear advantages and positive results involving internal and external actors in a collaborative scheme.**

Keywords*— *Learning Techniques, Design Methodologies, Rapid Product Realization Platforms, Education 4.0, Open Innovation.

I. Introduction

Today's society is undergoing constant changes at different social, economic and environmental levels. PriceWaterhouseCoopers, in a study titled "The World in 2050", stated that by the middle of the 21st century, there would be significant changes in the so-called emerging nations (E7) as a result of better social and economic conditions [1][2]. The paradigm shift in the global economic balance will increase the consumption of goods and services. It will be necessary to promote economic development in the different productive sectors by creating innovative tools, models, and structures that meet the growing population's needs [3]. This increased integration allows all sectors to benefit from the accelerated evolution of technology, driven primarily by increased computational power, such as artificial intelligence, robotics, data analytics, cloud computing and the internet of things. The growing adoption of technologies, mainly in industry, makes it possible to reinvent, redesign and integrate models that lead to a crucial evolution in manufacturing processes called Industry 4.0 [4]. There are numerous paths to integration in the medium and long term. In the academic field, to achieve this necessary transformation, it is necessary to integrate the technologies, tools and objectives set by the industry with the programs provided by the instruction centers. The productive sectors are constantly evolving and require professionals to address current problems and future challenges through specific skills and competencies, thus proposing innovative solutions that transform current paradigms. Education is undergoing a profound revolution to the extent that coming generations adopt new learning techniques that allow professionals to cope with the transformation of industry and services [5]. In this way, there is a continued effort for schools worldwide to transform their curricula to develop the skills and competencies demanded of students [6]. This radical transformation in learning is known as Education 4.0 and is the first giant leap to traditional education for decades. Integration is a fundamental part of this transformation; this is how the different productive sectors and even governments have developed different initiatives with education institutions to generate models and projects that benefit both parties. This two-way collaboration is a fundamental pillar of the growing adoption of the culture known as Open Innovation (OI). In this regard, this work gathers the approach taken by Tecnologico de Monterrey to lead the way in the education transformation to the extent driven by its Open Innovation Laboratory. This work is structured as follows. Section II briefly explores the concept of education 4.0 and how advances in technology applied to industry impact future professionals. The third section is about Open Innovation Laboratories (OIL) from the academia perspective and how it is structured to boost scholars' skills and competencies development. The fourth section details how OIL at Tecnologico de Monterrey is being used as a learning environment to foster experiences in the context of Education 4.0 and Open Innovation. Last but not least, the fifth section elaborates on three case studies in the context of OIL to observe a real-life deployment of the concept at Tecnologico de Monterrey.

II. Education 4.0 Overview

Education 4.0 has multiple definitions. One of them explores this concept as the adoption of novel methodologies and cutting-edge instruction spaces that completely change the paradigm of traditional education. This notion fosters better development of hard skills and provides further refinement of soft skills [7]. On the one hand, there is intense research that covers the set of skills needed in college students and on the other hand, they study the different methodologies and learning techniques to develop them. The industry's transformation has given way to defining the

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Semi-automatic simulation modelling. Results with Tecnomatix Portfolio in the automotive sector

Cortés, Daniel*. Ramírez, José*. Villagomez, Luis E.*. Batres, Rafael*. Velilla, Ailin**. Gonzalez, Emilio**. Puente, Jaime**. Esparza, Germán***. Cruz, Nancy***. Molina, Arturo*

*Tecnologico de Monterrey, School of Engineering and Sciences, Mexico City, Mexico
e-mail address: {a01655708, a00995924}@itesm.mx, {levg, rafael.batres, armolina}@tec.mx
**BOCAR Group, State of Mexico, Mexico
e-mail address: {ailin.velilla, emilio.gonzalez, jaime.puente}@bocar.com
*** Siemens Industry Software Inc., Mexico City, Mexico
e-mail address: {german.esparza_sedas, nancy.cruz}@siemens.com

Abstract: Nowadays, the influence of the Industry 4.0 concept has increased the use of technologies that allow systems to be connected and make decisions in a more efficient way to increase productivity and reduce expenses. Among Industry 4.0 portfolio, simulation allows the creation of scenarios to observe, analyze and forecast data within manufacturing facilities without investing in physical equipment. This technology has evolved over the decades and became of paramount importance to assist in decision making. However, the increased capabilities of simulation software cope with the growing complexity of modern production lines. Manufacturing flexibility demands continues changes that must be mirrored in simulation models forcing companies to invest resources in remodelling previous works; this is expensive and time-consuming. To address the continued development of manual simulations, a model is proposed to create fast, adaptable and instantiable semi-automated simulations. In this paper, there is presented the structure found while developing simulation models and, a proprietary solution to address shorter simulation cycles derived from the interaction within the industry. There are also achieved successful results for delving in the case study in the automotive sector. The main result when applying the model is pointed out in the time saved to semi-automate functional and reusable simulation models.

Keywords: Industry 4.0, Discrete event simulation, Decision systems, Model-driven systems engineering, Simulation cycle, Plant Simulation, Collaborative Network.

1. INTRODUCTION

Manufacturing systems are experiencing rapid transformations and undergoing profound changes aligned with Industry 4.0 continuous evolution. This is mainly driven by the synergy between different available technologies and boosted by the interconnectivity of Information and Communication Technologies (ICT). This integration provides the necessary tools to design, develop and deploy entire production lines, allowing better control of the lifecycle of the products and processes. Tighter controls in the production systems have a positive impact on reaching higher levels of productivity. However, the increasing complexity of the facilities come to hand by hand with the engineering needed on the planning, development and control phases.

Technologies like simulation modelling have been evolving according to industry demands and prove a valuable resource to address former challenges. Software solutions available in the market has become more complex and powerful, increasing the capacity for integration between the physical and digital worlds. Discrete event simulation (DES) software has been used to model this complex behaviour as it allows complete visualization and monitoring capabilities from individual parts to correlations between a group of components and processes (Promyoo, Alai, & El-Mounayri, 2019). To this regard, the increasing potential of DES software copes with the level of simulation detail needed in a modern industry where rapid changes in the market demand flexibilization of production lines. This urges to rapid modelling development where numerous variables associated increase the complexity of the job rendering model creation time-consuming. Current solutions provide a certain amount of design automatization; however, simulation modelling is not an automated process and the efforts to maintain paired the physical-digital world requires constant reengineering and adaptations of previous works.

Forecasting and optimization are common goals of simulation modelling. Specific results can be obtained if enough specs and variables are input to the model. Nonetheless, the deployment tends to be exclusive for a given scenario. For this reason, most of the time, this technology is only applied in large scale manufacturing facilities, thus, even with all its benefits, this technology is not always embraceable for use in small to medium enterprises. Then, automatic modelling creation has appeared as an interesting research area as it would reduce the effort and expertise needed in the production of simulations. This could lead to broader adoption of this tool for different industry sizes. In this paper, it is explained the design of a methodology for

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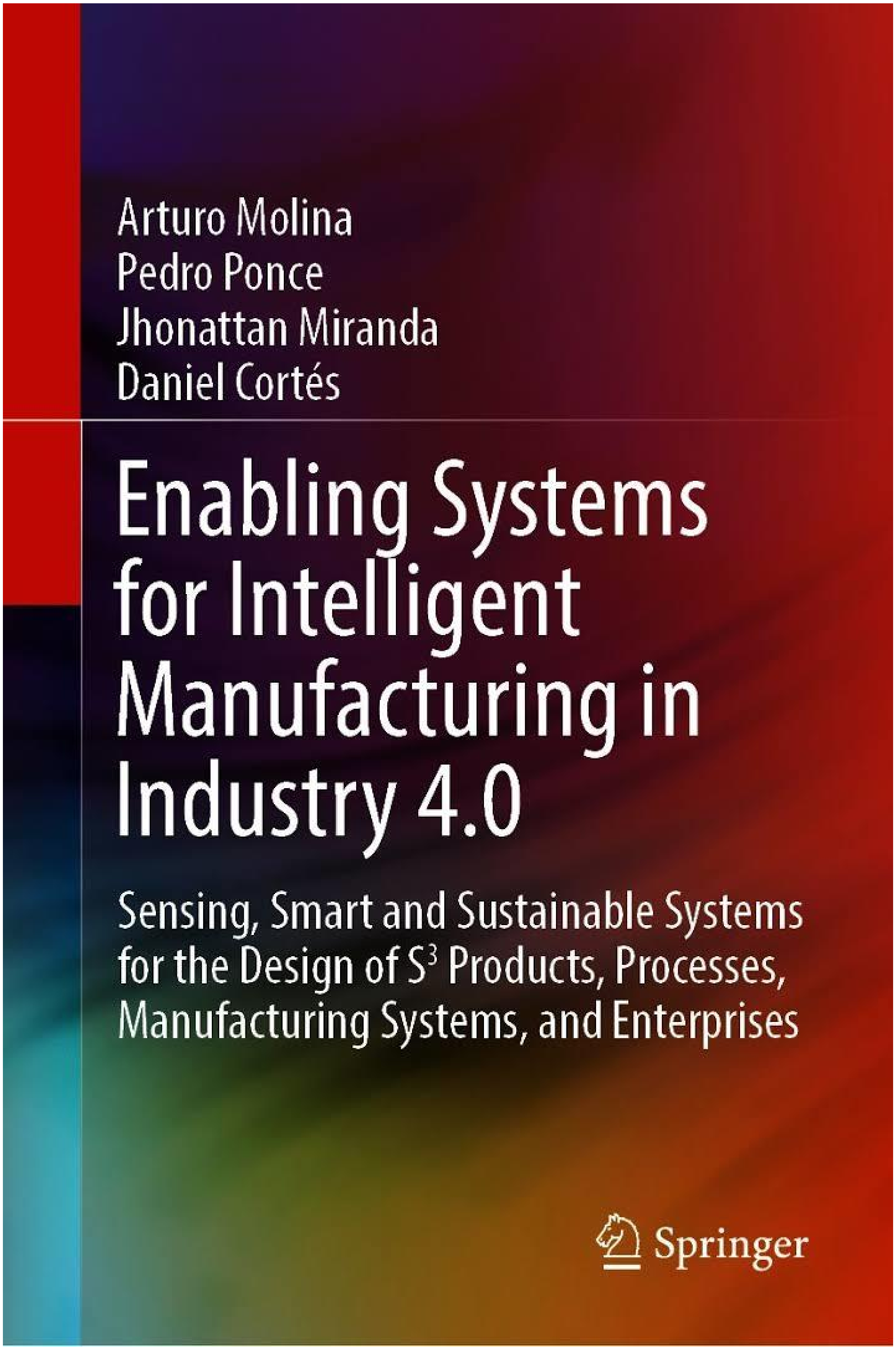

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S³ manufacturing process taxonomy

Daniel Cortés *, José Ramírez, Pedro Ponce, Arturo Molina

Escuela de Ingeniería y Ciencias, Tecnologico de Monterrey, Ciudad de México, 14380, Mexico

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ABSTRACT

In the literature, the design approach has been mainly focused on products, however, manufacturing process awareness lacks structure measurements of the organization resources and their productive capacity to systematize the adoption of newer technologies and automation of production lines. Due to this fact, there is a remaining gap in the adoption of technological resources to automate them. The study of manufacturing processes has made it possible to identify three opportunity areas in any type of organization: i) structured processes, ii) industrial environmental knowledge and iii) technological adoption. This article presents a taxonomy that structure available information in manufacturing processes into five levels to characterize, redesign, or develop them from scratch. To get a better comprehension of the environment, it is possible to enhance awareness of energy consumption, waste management, information flow and emissions control through Sensors, collection, processing, and communication of information through Smart components. The technological adoption goes hand in hand with the sustainable objectives of the organization and dictates the search for alternatives throughout the development or redesign of the manufacturing process to pursue economic, social and environmental objectives. Besides, the taxonomy was used in the characterization and updating of four manufacturing processes for a modular machine. These four case studies allow for better insight into the design process. The changes between the initial and final stages after the update were recorded in the S³ Scorecard to visualize the increase of the characteristics and to chart a route for future technological acquisitions. The proposal has made it possible to locate the characteristics of the manufacturing process at one level and align the objectives of the organization to a technology acquisition plan since manufacturing firms are looking to future-proof their investments by acquiring solutions to comply current regulations while maintaining low-cost operations.

1. Introduction

Nowadays, due to the increasing acceptance of technology in the productive sectors and the variety of existing solutions, organizations of all sizes are seeking the acquisition of systems that allow them to take control of their production chain. In the current market, multiple technologies complement each other such as cloud computing, mobile technologies, the internet of things, solutions that aim at diminishing distance barriers and allowing information sharing. By virtue of this, organizations are now more aware of what it takes to keep track, get short-term information, and the benefits of making decisions based on real-time information [1].

This fact derives mainly from the influence of the pillars of Industry 4.0 [2] and offering quality products and services to the communities. The inclusion of technologies has allowed establishing a direct conversation with the consumer and even consider their participation in the continuous improvement of organizations, breaking the traditional paradigm and turning it into a prosumer [3].

This is how manufacturing companies must perceive consumers as a fundamental piece that allows the diversification of current products or personalization of existing ones, offering a brand concept instead of just products. Manufacturing companies constitute an essential role as they generate jobs, growth in the region and professional opportunities for multiple areas. Nonetheless, Micro, Small and Medium Enterprises (MSMEs) still represent the working force capacity of developing countries. The main advantages of these manufacturing firms are the flexibility of their production lines [4] and the fast response to introduce novel products.

Although manufacturing firms offer opportunities in the region, they also seek to prevail over time and expand their markets. Therefore, they are looking for inventive personnel who know about techniques, methodologies and tools, capable of adapting new technologies to

* Corresponding author at: School of Engineering and Sciences, Tecnologico de Monterrey, Mexico City, 14380, Mexico.
E-mail address: a01655708@itesm.mx (D. Cortés).

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Integrated Product, Process and Manufacturing System Development for Multifunctional Micromachine Tool

Cortés, Daniel[a1*]; Ramírez, José[a]; Medina, Jorge[b]; Molina, Arturo[a].

[a] *Escuela de Ingeniería y Ciencias, Tecnologico de Monterrey, Ciudad de México, 14380, México.*

[b] *Departamento de Ing. Mecánica, Universidad de los Andes, Bogotá, 111711, Colombia.*

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ABSTRACT

Novel practices in the formation of students are encouraged to be multidisciplinary which in fact, allows them to better understand the behaviour of systems. This skill allows them to identify existing needs that impact multiple areas, both for an organization and to complement their entrepreneurial training. In this work, there is exposed a reference framework that arose to aid in the innovative design process among the manufacturing sector, it seeks to stretch the gap between conceptualization and implementation for engineering projects. Furthermore, the formation of the learners is enriched due to the breakdown of complex systems into entities as it gathers existing knowledge and provides structure to systematize the development process, allocate problems and provide feedback. Thus, design stages are detailed, engineering stages are described, and a toolbox is presented to guide designers into their task. The methodology has been tested under multidisciplinary projects in different time lapses, observing a positive impact in the formation of participants, as it guarantees the inclusion of desired attributes, documentation and milestones in the scenario being developed. In this article, there are described three case studies. Findings when developing using the methodology shows a structural, documented process followed by the designers, capable of recognizing the abilities acquired and reinforced skills, documented entities corresponding to what is developed at the end of the projects and time of deployment is enhanced.

Keywords
Integrated Product, Process and Manufacturing System Development
Manufacturing Process
Multifunctional Micromachine Tool
Plastic Extruder
3D Food Printer

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Author's contribution. **IPPMD reference framework. Two case studies are provided to support the realization of the work.**

1. Introduction

According to a Price Waterhouse Coopers article called "The World in 2050" (Price Waterhouse Coopers, 2015), most of the economic power will be transferred to the so-called Emerging Nations (E7) in the middle of the 21st century. This will result in profound transformations in their commerce, education and industry. An unprecedented increase in the consumption of goods and services will require innovative ways of producing them (Hehenberger, 2009). Innovation among the enterprises need to follow and respond faster to growing demands of novel, high quality and more personalized products as well as remain competitive in the globalized markets. Therefore, more than ever, enterprises must be aware of the challenging environment to assess and recognise

[1*] Corresponding author at: School of Engineering and Sciences, Tecnologico de Monterrey, Mexico City, 14380, Mexico.
E-mail address: a01655708@itesm.mx.

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Article

Integrating CAD/CAM/CAE/CAPP tools and Project-Based Learning to Mechanical Engineer training towards sustainable development

Roberto Pérez-Rodríguez [1,*], Carlos Alberto Trinchet-Varela [1], José Arzola-Ruiz [2], Pavel Michel Almaguer-Zaldivar [1], Rolando Esteban Simeón-Monet [1], Roberto Andrés Estrada-Cingualbres [1], Luis Wilfredo Hernández-González [1], Reynaldo Velázquez-Zaldivar [3], Jhonattan Miranda[4], Daniel Cortés[4], Arturo Molina[4] and Rafael Lorenzo-Martín [5]

[1] CAD/CAM Study Centre, University of Holguín, Campus "Oscar Lucero Moya", Holguín, Cuba
[2] CEMAT Study Centre, Technological University of Havana, Havana, Cuba
[3] Ministry of Higher Education, Havana, Cuba
[4] Tecnologico de Monterrey, Mexico City, México
[5] Directorate of Science, Technology and Innovation, University of Holguín, Campus "Oscar Lucero Moya", Holguín, Cuba
[*] Correspondence: roberto.perez@uho.edu.cu; Tel.: +53 58590346

Abstract: The generation of competencies for problem-solving and decision-making is one of the essential demands of the teaching of mechanical engineering in the second decade of the 21st century in the context of sustainable development. The increase in the application of information metrics, the Internet of things, virtual and augmented reality, Artificial Intelligence, etc., imply that the challenges are more diverse, complex and imprecise. The purpose of this article is to show a framework for the use of Project-Based Learning (PBL) and CAD / CAM / CAE / CAPP tools as dynamic resources in the comprehensive teaching of Mechanical Engineers in a context of sustainable development, all associated to industry. A systemic analysis of the variables that intervene in the framework, the stages and the partial results of its application in two academic years is carried out. The main contributions shown is an appropriate framework for the use of PBL and computer aided tools as resources in the development of professional competencies of Mechanical Engineers in a context of sustainable development. The results confirmed the student's achievement in getting the professional competencies in contemporary contexts.

Keywords: active methodologies; project-based learning (PBL); mechanical engineering; CAD/CAM/CAE/CAPP; professional competencies; sustainable development

1. Introduction

The demands imposed by the accelerated progress of technologies (which includes massification, globalization, marketing and digitization), imply that sustainable development is a complex and comprehensive goal. In this context, higher education institutions are agents of change, which must adapt and reinvent themselves in various settings [1, 2].

The United Nations General Assembly, in 2015, approved the resolution that established the 2030 Agenda [3]. This resolution conceptualizes the term Sustainable Development, establishing 17 sustainable development goals (SDGs). In this way, a framework of reference was structured for its practical application. Education for Sustainable Development (ESD) is part of SDG 4: High-quality education [1].

Sustainable development is a concept applied in various fields, from public policies, research projects, to the general population. As a trend, it is fundamentally related to climate change and inequalities in socio-economic development. At the university level [4-

Short bio of the author

Daniel Cortés graduated as an Industrial Chemical Engineer. Later he completed a Master's Degree in Business Administration within the Instituto Politécnico Nacional. In 2017 he entered the Philosophy Doctor in Engineering Sciences program at Tecnológico de Monterrey. As a professional experience, he has worked in analytical chemical analysis laboratories, in the application of quality management standards regarding research and educational development, conducting physicochemical tests to ensure quality in the cosmetic industry, as a business consultant in a company dedicated to the production of foods derived from corn and, as an engineering logistics and management analyst for project implementation in a communications company. As research projects, he collaborated in a binational project with Universidad de los Andes for the development of a 3D food printer, in the simulation of discrete event simulation projects with a tier-one supplier company in the automotive sector, in the design of a consultation platform to collect information about Sustainability facilities at Universitas 21 and in the technological maturation of the micromachine to include new functionalities and a modular design for educational and professional purposes. Among his research works, he has participated in the co-authorship of 19 scientific products, including participation in international forums, conferences, magazines, and a book's publication.

In this work, his doctoral contribution to the Sensing, Smart and Sustainable Process Development Reference Framework is presented, whose main objective is to narrow the existing gap for the development of manufacturing processes and provide a methodology that contributes to migrating traditional to automated manufacturing processes for sustainable purposes, a vision raised in the concept of Industry 4.0. It contributes to the state of the art in developing manufacturing processes. It is intended to be used by manufacturing process developers in any size of the industry. The contribution includes a generic model for the study of variables, the reference framework with the activities to be implemented, the levels of the solutions in a taxonomy, the practical toolbox for the industrial sector and the methodology to carry them out in a structured manner.