ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

# QUALITY IMPROVEMENT OF ADDITIVE MANUFACTURING PROCESSES THROUGH LEAN

JUAN CARLOS GARCÍA LÓPEZ

TRABAJO DE FÍN DE GRADO

Madrid

Junio 2018

UNIVERSIDAD PONTIFICIA
ICAI ICADE
COMILLAS
MADRID

**AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN ACCESO *ABIERTO* (*RESTRINGIDO*) DE DOCUMENTACIÓN**

***1º. Declaración de la autoría y acreditación de la misma.***

El autor D. Juan Carlos García López, como estudiante de Grado en Ingeniería Electromecánica de especialidad mecánica de la UNIVERSIDAD PONTIFICIA COMILLAS (COMILLAS), **DECLARA**

que es el titular de los derechos de propiedad intelectual, objeto de la presente cesión, en relación con la obra Proyecto Fin de Grado titulado QUALITY IMPROVEMENT OF ADDITIVE MAUFACTURING PROCESSES THROUGH LEAN, que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual como titular único o cotitular de la obra.

En caso de ser cotitular, el autor (firmante) declara asimismo que cuenta con el consentimiento de los restantes titulares para hacer la presente cesión. En caso de previa cesión a terceros de derechos de explotación de la obra, el autor declara que tiene la oportuna autorización de dichos titulares de derechos a los fines de esta cesión o bien que retiene la facultad de ceder estos derechos en la forma prevista en la presente cesión y así lo acredita.

***2º. Objeto y fines de la cesión.***

Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad y hacer posible su utilización de *forma libre y gratuita* ( *con las limitaciones que más adelante se detallan*) por todos los usuarios del repositorio y del portal e-ciencia, el autor **CEDE** a la Universidad Pontificia Comillas de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución, de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra (a) del apartado siguiente.

***3º. Condiciones de la cesión.***

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia, el repositorio institucional podrá:

Transformarla para adaptarla a cualquier tecnología susceptible de incorporarla a internet; realizar adaptaciones para hacer posible la utilización de la obra en formatos electrónicos, así como incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.

(a) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato. .

(b) Comunicarla y ponerla a disposición del público a través de un archivo abierto institucional, accesible de modo libre y gratuito a través de internet.[1]

(c) Distribuir copias electrónicas de la obra a los usuarios en un soporte digital. [2]

***4º. Derechos del autor.***

El autor, en tanto que titular de una obra que cede con carácter no exclusivo a la Universidad por medio de su registro en el Repositorio Institucional tiene derecho a:

a) A que la Universidad identifique claramente su nombre como el autor o propietario de los derechos del documento.

b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.

c) Solicitar la retirada de la obra del repositorio por causa justificada. A tal fin deberá ponerse en contacto con el vicerrector/a de investigación (curiarte@rec.upcomillas.es).

d) Autorizar expresamente a COMILLAS para, en su caso, realizar los trámites necesarios para la obtención del ISBN.

d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

(d) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato. .

(e) Comunicarla y ponerla a disposición del público a través de un archivo abierto institucional, accesible de modo libre y gratuito a través de internet.[1]

(f) Distribuir copias electrónicas de la obra a los usuarios en un soporte digital. [2]

***4º. Derechos del autor.***

El autor, en tanto que titular de una obra que cede con carácter no exclusivo a la Universidad por medio de su registro en el Repositorio Institucional tiene derecho a:

e) A que la Universidad identifique claramente su nombre como el autor o propietario de los derechos del documento.

f) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.

g) Solicitar la retirada de la obra del repositorio por causa justificada. A tal fin deberá ponerse en contacto con el vicerrector/a de investigación (curiarte@rec.upcomillas.es).

h) Autorizar expresamente a COMILLAS para, en su caso, realizar los trámites necesarios para la obtención del ISBN.

d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

---

[1] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría redactado en los siguientes términos:

(c) Comunicarla y ponerla a disposición del público a través de un archivo institucional, accesible de modo restringido, en los términos previstos en el Reglamento del Repositorio Institucional

[2] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría eliminado.

***5º. Deberes del autor.***

El autor se compromete a:

a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.

b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.

c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.

d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

***6º. Fines y funcionamiento del Repositorio Institucional.***

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

a) Deberes del repositorio Institucional:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.

- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusiva del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.

- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.

Derechos que se reserva el Repositorio institucional respecto de las obras en él registradas:

- Retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 04 de Junio de 2018

**ACEPTA**

Fdo……………………………………………………………

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

QUALITY IMPROVEMENT IN ADDITIVE MANUFACTURING PROCESSES THROUGH LEAN

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2017/2018 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada

de otros documentos está debidamente referenciada.

Fdo.: Juan Carlos García Fecha: 03 / 06 / 2018

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fecha: 27/ 07 / 2018

**QUALITY IMPROVEMENT OF ADDITIVE MANUFACTURING PROCESSES THROUGH LEAN**

**AUTOR: García López, Juan Carlos**

ADVISOR : Becker, J.M.J.

ENTIDAD COLABORADORA: University of Twente

SUMMARY OF THE PROJECT:

**Introduction:**

The constant emergence of innovative techniques of rapid prototyping and three-dimensional printing in the industrial sector, has generated a real revolution in the sector that has made many companies and institutions join the use of these for their own benefit, whether purely economic or simply useful. for the proper development of their professional activity. Its rapid adoption has taken manufacturing to a stage full of advantages compared to previous moments in the sector, such as accessibility to manufacturing under demanding conditions (such as space1 or the desert) or the smaller physical space needed to manufacture.

However, and although the professional environment requires the adoption of cutting-edge manufacturing techniques such as Selective Laser Sintering and Extrusion of material in an agile manner to achieve real competitiveness, companies must approach such adoption with moderation due to the need to adapt of workspaces that, both technically and culturally, continue to be linked to traditional manufacturing methods.

The change or addition of an interlaced system of 3D printing, by its very nature, involves the emergence of a series of problems that may not have been taken into account since the implementation, such as the direct influence of temperature on the quality of the manufactured product, the need for real isolation to generate biological tissue, or even the inexperience of the staff. That is why the choice of a system or methodology to attack these problems based on continuous improvement such as the Lean philosophy, seems entirely correct, especially if one takes into account the success of this philosophy in large companies already established .

It seems reasonable to also point out the importance of adapting the available physical space both structurally and by adapting environmental factors such as temperature and humidity. That is why the need to develop an action plan should not be overlooked, weighing the economic impact that such changes may imply.

**Objectives**

The purpose of this project is the application of Lean Manufacturing philosophy and processes to an environment dedicated to 3D printing, and the subsequent delivery of plans of a workstation adapted as it complies with Lean standards and contributes to the reduction of surface Useful dedicated. The study is therefore focused on a typical institution: the company belonging to the University of Twente (The Netherlands) that satisfies the demand for prototyping by additive manufacturing for customers in the region.

**Methodology**

To get a detailed study, the report begins by reviewing the news regarding additive manufacturing and Lean independently.

Taking into account the concept of waste introduced by Shigeo Shingo in the 60s, the sources of inefficiency and waste of a 3D printing center are analyzed, which has the main printing types as of January 2018, from the request by the client to the final delivery of the finished product / prototype. The method for this analysis is based on the guidelines of the Lean Enterprise Institute that aims to standardize the Lean adaptation processes and considers the need to elaborate a series of reports: CTQ Flow Down, SIPOC diagram and fishbone diagram.

Later, the structural and mechanical design of a workstation based on a pilot project (University of Twente) is started while selecting those Lean tools that are appropriate in the case study and should be implemented and reflected in the new workspace .

Finally, the impact of the implementation of the system on the day-to-day of the 3D printing center is evaluated and the economic and sustainability impact it will have for the organization is assessed.

**Results**

The main problems detected in the processes are human and environmental failures, which are accentuated by constant breakdowns, reprocesses and incidents, which are repairable through this new approach.

One of the most relevant conclusions is that to improve the production of an additive manufacturing centre, it does not require cutting-edge technology or an overly high investment, but rather to identify the sources of the problem in a systematized way (such as times that do not add value ) and eradicate them, converting the process into a clean and flawless manufacturing.

The subsequent improvements, due to its cultural component. will only be achieved through a real commitment of all the people that make up the company, from the people in charge to the workers. In order to function as a sustainable company, it is essential to apply all the techniques exposed in this thesis as a whole and not in isolation.

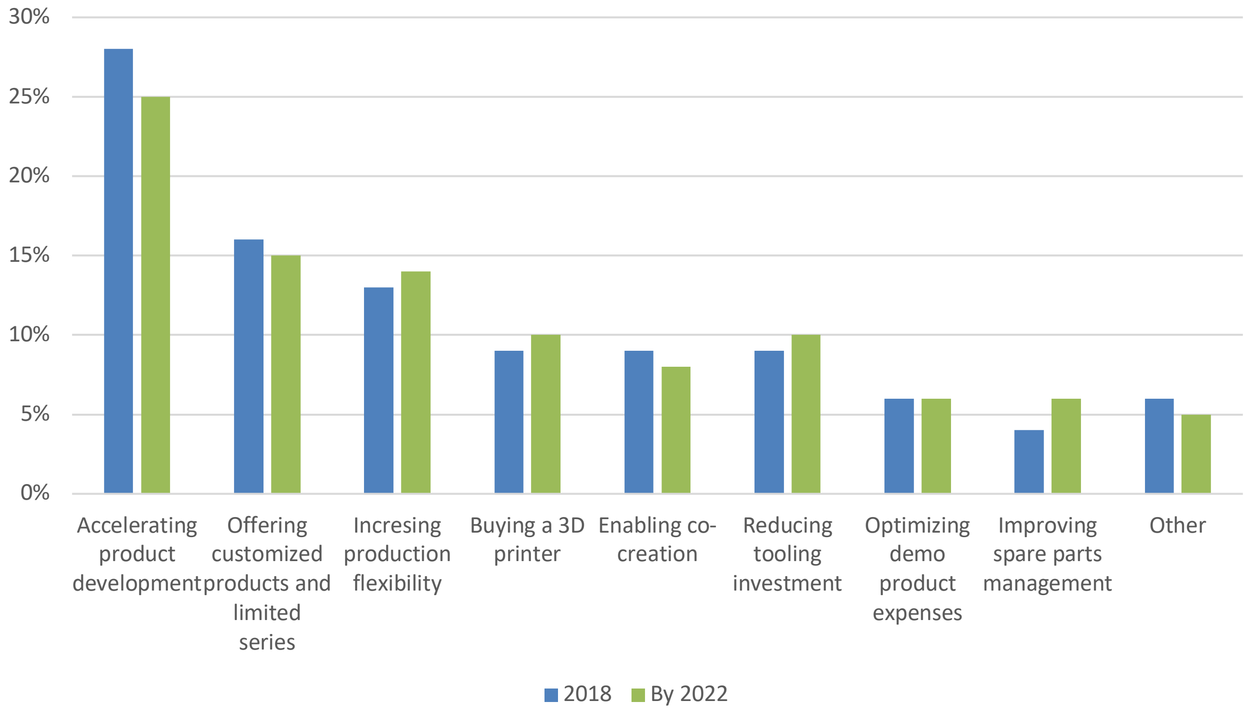



**Figura 1. El gráfico muestra la perspectiva de evolución de las principales aplicaciones y potenciales usos de la impresión 3D en el sector industrial**

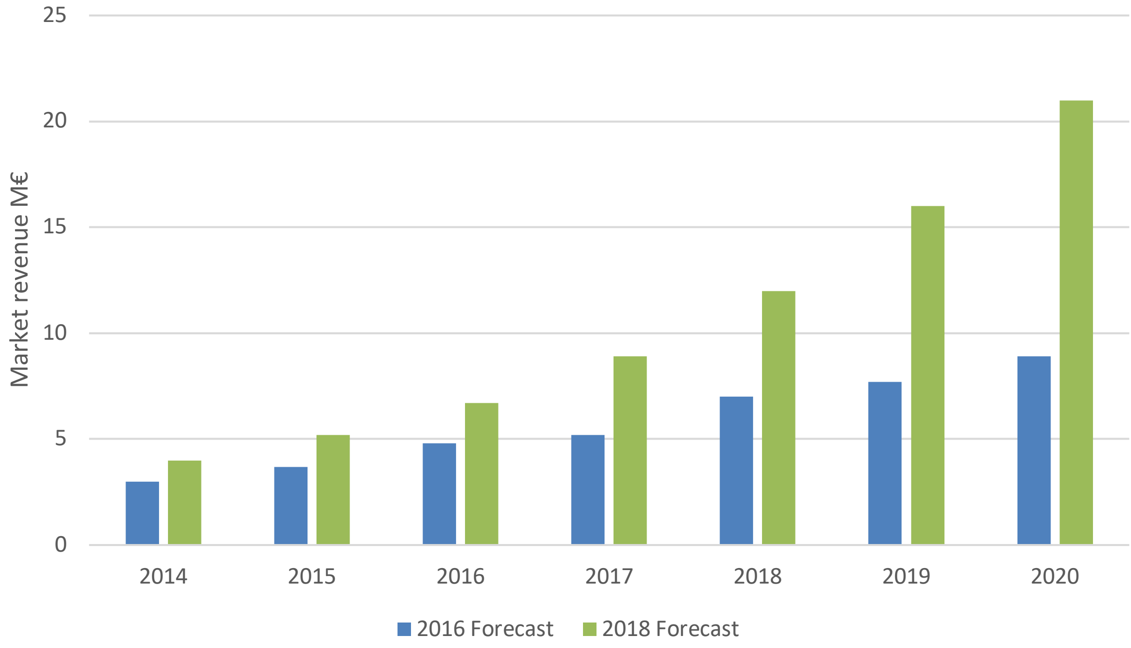



**Figura 2. Este gráfico muestra el incremento vertiginoso de la previsión de crecimiento del sector de fabricación aditiva**

## Conclusions

The exciting aspiration of additive manufacturing as an off-road manufacturing technique, leads traditional companies to have to adapt both their machinery and their personnel to be competitive. This adaptation must not be unstructured, but aimed at optimizing the manufacturing process to achieve high customer loyalty.

The results that this study aims to offer are valid both for a limited manufacturing environment such as the laboratory of a large university, and for a company dedicated purely to manufacturing. The final design of the solution implemented at the University of Twente is scalable to any other center with a space dedicated to 3D printing with at least 10 m2 available.

RESUMEN DEL PROYECTO:

La constante irrupción de novedosas técnicas de prototipado rápido e impresión tridimensional en el sector industrial, ha generado una verdadera revolución en el sector que ha hecho que muchas compañías e instituciones se sumen al uso de estas para beneficio propio, ya sea puramente económico o simplemente útil para el correcto desarrollo de su actividad profesional. Su rápida adopción ha llevado la fabricación a un escenario repleto de ventajas respecto a momentos anteriores del sector, como la accesibilidad a manufactura en condiciones exigentes (como el espacio[1] o el desierto) o el menor espacio físico necesario para fabricar.

Sin embargo, y aunque el entorno profesional exige la adopción de técnicas punteras de fabricación como el Sinterizado selectivo por láser y la Extrusión de material de manera ágil para alcanzar una competitividad real, las empresas deben enfocar dicha adopción con mesura debido a la necesidad de adaptación de espacios de trabajo que, tanto técnica como culturalmente siguen ligados a los métodos de fabricación tradicional.

El cambio o adición de un sistema entrelazado de impresión 3D, por su propia naturaleza, conlleva la irrupción de una serie de problemas que pueden no haberse tenido en cuenta desde la implantación, como la influencia directa de la temperatura en la calidad del producto fabricado, la necesidad de un aislamiento real para generar tejido biológico, o incluso la propia inexperiencia del personal. Es por ello, que la elección de un sistema o metodología de ataque a estos problemas basada en la mejora continua como la filosofía Lean, parece del todo acertada, sobretodo si se tiene en cuenta el éxito de esta filosofía en empresas de gran tamaño ya establecidas.

Parece razonable también señalar la importancia de adaptación del espacio físico disponible tanto estructuralmente como mediante la adecuación de factores ambientales como la temperatura y la humedad. Es por ello que no debe obviarse la necesidad de elaborar un plan de acción, sopesando el impacto económico que dichos cambios puedan suponer.

## Objetivos

El propósito de este proyecto es la aplicación de la filosofía y procesos Lean Manufacturing a un entorno dedicado a la impresión 3D, y la posterior entrega de planos de una estación de trabajo adaptada a medida que cumpla con estándares Lean y contribuya a la reducción de superficie útil dedicada. El estudio se centra por tanto en una institución tipo: la empresa perteneciente a la Universidad de Twente (Holanda) que satisface la demanda de prototipado mediante fabricación aditiva para clientes de la región.

## Metodología

Para conseguir un estudio en detalle, el informe comienza revisando la actualidad en cuanto a fabricación aditiva y Lean de manera independiente.

Teniendo en cuenta el concepto de desecho implantado por Shigeo Shingo en los años 60, se analizan la fuentes de ineficiencia y desperdicio de un centro de impresión 3D que cuenta con los tipos principales de impresión a fecha de Enero 2018, desde la solicitud por parte del cliente a la entrega final del producto/prototipo terminado. El método para dicho análisis, se basa en las directrices del Lean Enterprise Institute que pretende estandarizar los procesos de adaptación a Lean y contempla la necesidad de elaborar una serie de informes: CTQ Flow Down, diagrama SIPOC y diagrama de espina de pez.

Más adelante, se comienza el diseño estructural y mecánico de una estación de trabajo basada en un proyecto piloto (Universidad de Twente) mientras se seleccionan aquellas herramientas Lean que son adecuadas en el caso de estudio y deben implantarse y reflejarse en el nuevo espacio de trabajo.

Finalmente, se evalúa el impacto que tendrá la implantación del sistema en el día a día del centro de impresión 3D y se valora el impacto económico y de sostenibilidad que tendrá para la organización.

**Resultados**

Los principales problemas detectados en los procesos son fallos humanos y ambientales, que se acentúan por constantes averías, reprocesos e incidentes, que son reparables a través de este nuevo enfoque.

Una de las conclusiones más relevantes consiste en que para mejorar la producción de un centro de fabricación aditiva, no se requiere tecnología de vanguardia ni una inversión exageradamente alta , sino identificar las fuentes del problema de una forma sistematizada (como los tiempos que no añaden valor) y erradicarlas, convirtiendo el proceso en una fabricación limpia y sin defectos.

Las posteriores mejoras, debido a su componente cultural. solo se lograrán mediante un compromiso real de todas las personas que componen la empresa, desde los responsables hasta los trabajadores. Para poder funcionar como una empresa sostenible, es esencial aplicar todas las técnicas expuestas en esta tesis como un todo y no de forma aislada.

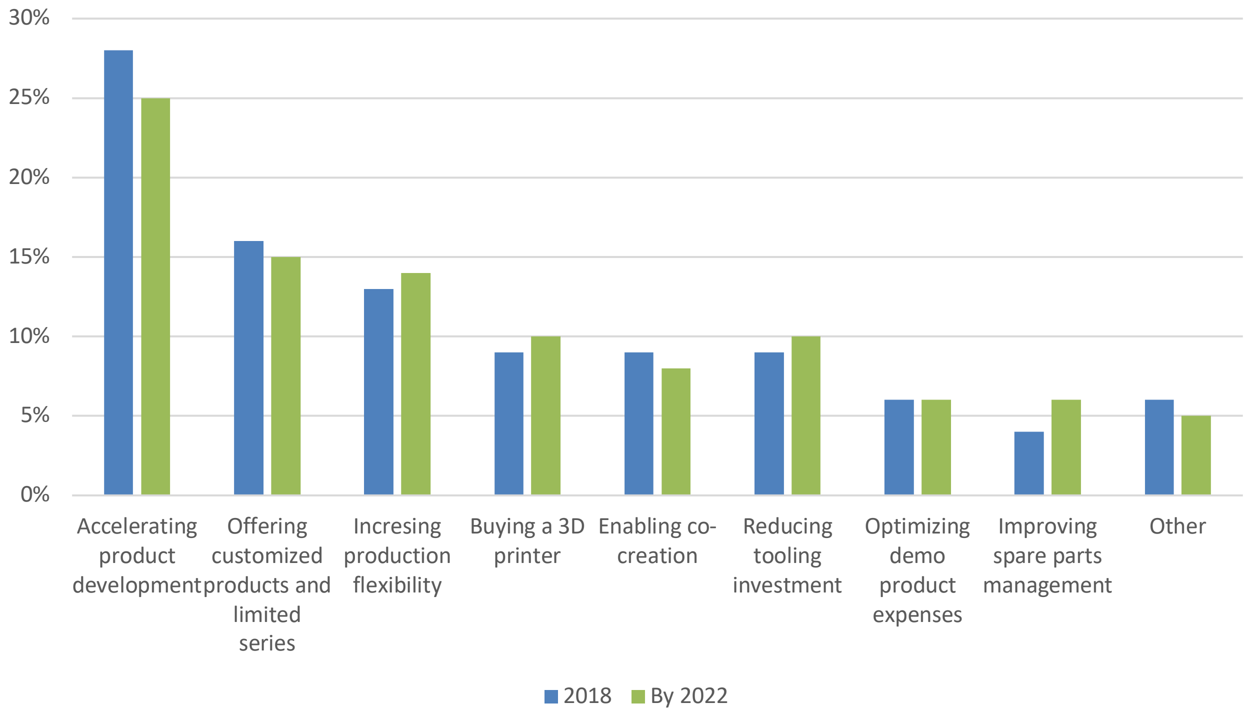



**Figura 1. El gráfico muestra la perspectiva de evolución de las principales aplicaciones y potenciales usos de la impresión 3D en el sector industrial**

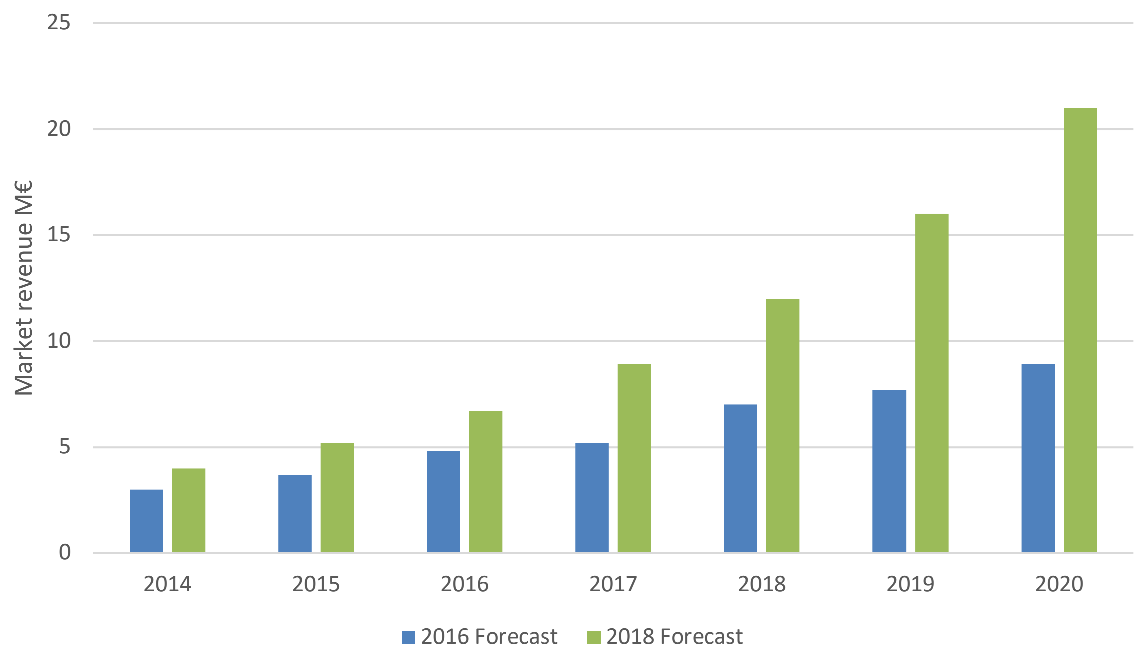



**Figura 2. Este gráfico muestra el incremento vertiginoso de la previsión de crecimiento del sector de fabricación aditiva**

## Conclusiones

La aspiración trepidante de la fabricación aditiva como técnica de fabricación todoterreno, lleva a las empresas tradicionales a tener que adaptar tanto su maquinaria como su personal para ser competitivos. Está adaptación no debe ser desestructurada, sino orientada a optimizar el proceso de fabricación para conseguir una alta fidelidad de clientes.

Los resultados que este estudio pretende ofrecer, son válidos tanto para un entorno limitado de fabricación como puede serlo el laboratorio de una universidad de gran tamaño, como para una empresa dedicada puramente a la manufactura. El diseño final de la solución implantada en la University of Twente, es escalable a cualquier otro centro con un espacio dedicado a la impresión 3D con, al menos 10 $m^2$ disponibles.

## Referencias

[1] Quincy Bean. *NASA*, "3D Printing in Zero-G Technology Demonstration" June 2017. Avaliable at: https://www.nasa.gov/mission_pages/station/research/experiments/1115.html

# INDEX OF CONTENTS

# ILLUSTRATIONS INDEX

# TAB INDEX

# 1. DESCRIPTIVE MEMORY

## 1.1 MOTIVATION

It has already been stated that every laboratory, specialized either in 3D Printing or traditional processes, has different problems that affect quality of the final product and the value chain. It is, therefore, a crucial matter, to identify and troubleshoot these inefficiencies. Since the majority of the 3D Printing companies and laboratories use all, or nearly all, of the techniques to be able to manufacture every demandable part, it seems reasonable to develop a general and tangible solution for eliminating the main sources of problems they might find.
The aim of this project is to develop a systematic approach to the main inefficiencies found in 3D Printing laboratories, such as material loss, wasted time or vast energy consumption from a mechanical point of view and then design a physical workstation and an action plan that troubleshoots the main problems an additive manufacturing laboratory/company may encounter.

3D Printing, contrary to what may seem, is a process that involves different actors, materials, environmental conditions and machinery and that is why a Lean approach to troubleshoot every problem, inefficiency or waste the laboratory may face is more than suitable.

The University of Twente is proud to constitute the biggest campus in Europe. However, the space optimization is crucial to ensure continuous improvement and adoption of laboratories that develop the most up-to-date technologies, so the designed solution bust will be spatially constrained. The Additive Manufacturing Laboratory works as an independent laboratory that, apart from serving as a research centre, works for external companies in the Overijssel region by serving them with 3D Printed prototypes.

This thesis, also aims to give a general point of view of how a general Additive Manufacturing laboratory should meet the quality requirements of any client, but using the University of Twente laboratory as a pilot project and as the statistical sample where the data is obtained.

One of the major drawbacks of additive manufacturing is the vast amount of techniques and printers that can be used depending on the purpose of the part and the material used in the process. It is, therefore, necessary to design a convergent solution for the previously mentioned laboratory, that can be scaled up after to a general use. This solution will be a personal design that will meet the mechanical and dimensional criteria imposed by a generic industrial laboratory (security, cleanliness, order…).

## 1.2 GOALS

Over the last few years, the Lean philosophy and methodologies have arisen as the main efficiency goals for every industry, independently on the size or the production capacity.

Technical goals:

- Design a specific bespoke and space-constrained workstation that serves as a solution to the problems that the University of Twente laboratory may find: waste of space, defective parts due to inadequate temperature, sudden mechanical movements, bad calibration of the machinery or defective supply material.
- Give a general solution to reduce exhaustively the main inefficiencies of the Additive Manufacturing processes in a generic laboratory either from a University or from a company.

Learning goals:

- To deepen the knowledge into the 3D Printing world and techniques.
- To broaden the knowledge about current additive manufacturing problems and the lines of investigation ongoing to solve them.
- To broaden the knowledge about Lean to a level where I am able to apply it in a professional environment.
- To use Lean philosophy to overcome technical challenges associated to 3D Printing from the product development until the final product delivery.

## 1.3 METHODOLOGY

1. *Election of sample and problem identification:* before the elaboration of any kind of report, personal interviews with people in charge of both the 3D Printing and Lean Manufacturing departments at the University of Twente should be carried out. These key actors will expose the problem from a personal and, therefore, extremely valuable point of view. Information from first hand will lead to the elaboration of the first list of sources of waste and will make the problem comprehensible. These interviews will also allow to gather both qualitative and quantitative data which will, later, be the basis for a correct election of involved variables.

2. Research: two lines of investigation will follow the problem identification and will constitute the first part of the report:

    1. Investigation about Additive manufacturing, its needs and mechanical requirements, techinques and processes involved:

| ANALYZED TECHNIQUES | |
|---|---|
| Selective Laser Melting | Directed Energy Deposition |
| Electron Beam Melting | Material Extrusion |
| VAT Polymerization | Sheet Lamination |
| Binder Jetting | Material Jetting |

    2. Investigation about Lean philosophy, Lean manufacturing and Lean product development.

3. *Variable definition:* key indicators that are to be analysed must be measurable, controllable and modifiable. These indicators serve as the solid basis to elaborate a

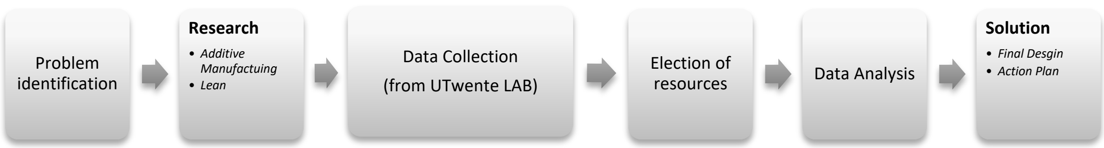
final solution. Examples of them are: environmental temperature of the laboratory room, number of defective parts per year that are produced in the laboratory or, even, number of electricity cuts per time period that affect the productivity.

4. Election of resources: every material or non-material tool needed to design a final solution must be listed in advance and refreshed if required because of the irruption of new problems.

5. Analysis of gathered data: statistical analysis of the raw data gathered to understand the problem/s must be carried out. Subsequently, data visualization should naturally derive into the numerical problem identification and what key points or steps of the process should be troubleshot.

6. Design of solution: After the data collection and proper analysis of the raw facts and information, a main step will be carried out:

    - Design of an action plan to ensure a correct Lean adaptation of the laboratory and its workforce.



## 1.4 LITERATURE REVIEW

### INTRODUCTION TO ADDITIVE MANUFACTURING

If we look at the history of production, Metal Forging has been around for 7000 years, but is still used, researched and improved today. Metal Turning is a lot younger, while more complex processes like Milling or more energy intensive processes like Extrusion are, relatively speaking, only a few hundred years old.

Additive manufacturing is very much linked to computer power, so its irruption was linked to computers becoming widely available. But, still, the first additive manufacturing processes have been developed for the last 32 years.

Additive manufacturing has different names depending on the author and the context. Rapid Prototyping (create a prototype quickly); Rapid manufacturing (create functional products quickly under yield strength, accuracy or material demands); Layered manufacturing (build a product layer by layer); Additive manufacturing (create a product by adding material, not removing it like turning or milling) or, the most popular, 3D Printing (printing material in height, opposing to the regular ink paper printing). However,

In recent years, metal became also available as a printing mater. It again formed a big hype, but is not as new as commonly suggested, actually metal has been printed all over the world for years before that. Companies already had worn down their first metal printer and bought their second one, before 2005. There is a real media hype on 3D printing; some is new, but most of it is not.

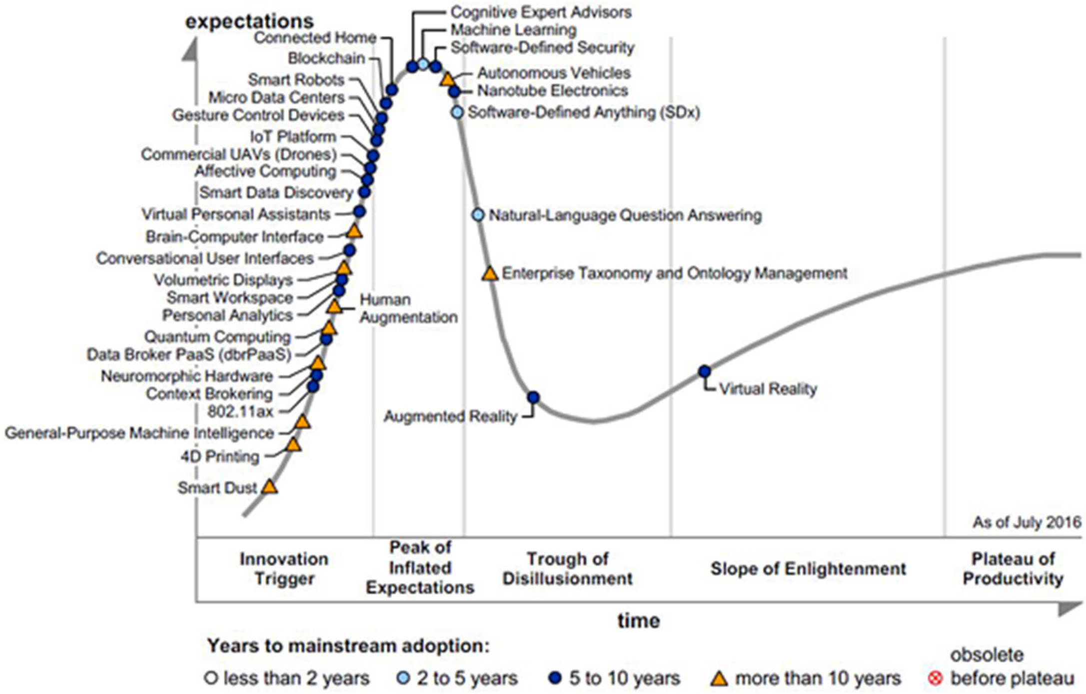



Fig. 1 - Gardner hype curve for new technologies 2016 [Source: Gartner Institute]

Additive manufacturing as we know it nowadays is recent, but will have large impact on production and is, still, constantly developing. The processes are not mature either. For example, the first fatigue test for AM produced parts emerged in late 2014. Therefore, fatigue behaviour for these additive manufactured parts is still unknown. Standards, norms and certifications are currently (2017) being developed and new process variants are developed each year.

### *Material extrusion*

Material extrusion is the printing process par excellence. The word extrusion comes from the Latin "extruder" which means to force a material through a hole. The extrusion consists of passing under the action of the pressure of a partially liquidified material through a device with more or less complex form (spinneret), in such a way, and continuous, that the material is in a cross section equal to that of the orifice. In the extrusion of thermoplastics the process is not so simple, since it is the same, the polymer is melted inside a cylinder and later, cooled in a soil, This extrusion process has as objectives, a process that is continuous the production of profiles , tubes, plastic, plastic sheets, etc.

### *Material jetting*

Material Jetting has the same working principle as a 2 dimensional inkjet printer, with the only difference in the way material is deposited. In Material Jetting layers of liquid photopolymers are jetted into a build tray where are instantly cured by a UV light. Building a part starts by jetting material into the build tray. The jets are followed by UV light, which instantly accumulated on the tray, creating a precise object. Where supports are required, usually with overhangs and complex shapes, a removable gel-like support material is temporarily used. After the print has completed this support material can be removed.

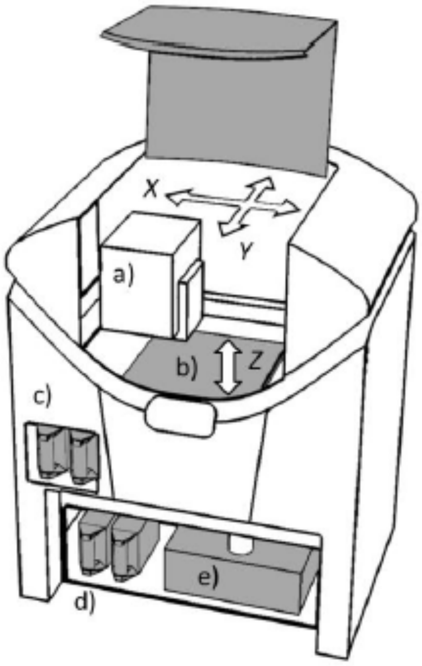



**Fig. 2 – Regular material jetting system**

Fig.2 gives the operating principle of multi-material jetting systems and the main components according to Baumers M. et al. (BAUM12)

Within an enclosed build volume, shown here with its cover open, photopolymer droplets are deposited by a nozzle:(a) onto a build platform (b). Moving in the in the X / Y plane. The print head also incorporates a UV light source to initialize a polymerization reaction and a planarization mechanism to remove excess material. After finishing the deposition of material and UV exposure within a layer, the build platform indexes down by one increment in the Z direction and the deposition process for the next layer begins. Fresh build material is fed to the jetting head from multiple material cartridges (c), each one containing a separate build material. An additional material required for the deposition of sacrificial structures

connecting parts to the build plate and to support overhangs is supplied from support material cartridges (d). The excess material removed during the build process by planarization is transferred into a waste container (e). This build cycle is repeated layer-by-layer until the build operation is complete and the platform (b) can be removed by the machine operator.
Because of their preciseness, this makes them advantageous for application within medical field, e.g. bioprinting.

Inkjet printing can operate either in continuous (CIJ) or drop on demand (DOD) mode. In CIJ mode the printer is operated in a continuous stream mode at very high speeds which results in low printing quality and it is mainly used for high speed graphical applications (GANS04). When using DOD mode, the droplets of a solution are jetted only according to the requirements and are perfectly located on predetermined position. Depending on the technology, inkjet printing is categorised into thermal, piezoelectric, acoustic or electrostatic inkjet.

In electrostatic inkjet printing, the ink is conductive and is mounted to a plate electrode where voltage is applied between the plate and the ink chamber, which lead the drop. In thermal inkjet printing the ink is heated, by means of a thin film resistor of heater which is activated through an electrical pulse and thus creating a rapidly expanding vapour bubble which in turn ejects the ink from the nozzle. The piezoelectric dispensers, on the other hand, rely on the deformation of a piezoelectric material. Piezoelectric ink-jetting is the most researched technique nowadays, due to its flexibility regarding the ink compatibility and the higher range in the operation frequency over thermal ink-jetting.

### *Powder bed fusion*

Powder Bed Fusion uses powder material in a vat in which heat is applied locally to solidify the parts, either by using laser, by an electron beam or by oven sintering.

SLS and SLM are the most used processes for functional parts. With that material characteristics and material behaviour is important. Although all materials will behave differently, some trends are there. Some examples will be given for metals and plastics.

Powder bed fusion (PBF) is one of the first additive manufacturing processes that is commercialized. The university of Texas was the first to commercialize the Selective Laser Sintering Technique (SLS). Powder bed fusion is based on the use of one or even more thermal sources that enhance fusion of powder particles in one layer at the powder bed and the products are build layer by layer. When all the particles in a layer are fused together, a new layer of powder is applied. The melted material solidifies when the temperature lowers. When the build is finished the unsintered powder is removed. This rapid prototyping process can be used for a wide range of materials (polymers, metals, ceramics and composites).

As mentioned before, laser sintering and laser melting are the two main techniques of powder bed fusion. The different kinds of sintering are explained, first the definition of sintering; sintering is a method to create objects out of powders by applying thermal energy on materials like ceramics, metals or plastics. In fact it is one of the oldest techniques that is used by humans, it is used in the prehistoric era with the firing of pottery.

There can be made a distinction between two different types of sintering: solid state sintering and liquid phase sintering. Solid state sintering is a sinter process that is below the melting temperature and occurs when the powder is densified wholly in a solid state at the sintering temperature. Various different physical and chemical reactions occur during the sintering. The most important one is diffusion. It involves neck formation between powder particles, this can be seen in figure 2. The main advantage of solid state sintering is that a wide variety of materials can be processed. It is a slow process and therefore it is necessary to preheat the powder to achieve a high rate of diffusion rate.

During liquid phase sintering or also called partial melting, a liquid phase coexists with solid material at a certain sintering temperature. You can say that a part of molten powder is spread between solid particles The existed liquid phase enhances the interparticle bonding. An example of liquid phase sintering is a system with two component powder, powder with a low melting material and a high melting material. As first the low melting material phase melts and the high melting material stays solid. The solid powder is bonded together by the melt.

Another type of sintering is full melting. Full melting is the most common technique in powder bed fusion, also known as selective beam melting. During melting the entire material subjected to heat is molten to a depth of one layer. Full melting is very effective to create well-bonded and high density structures. Full melting has the advantage that it creates full dense products in one go.

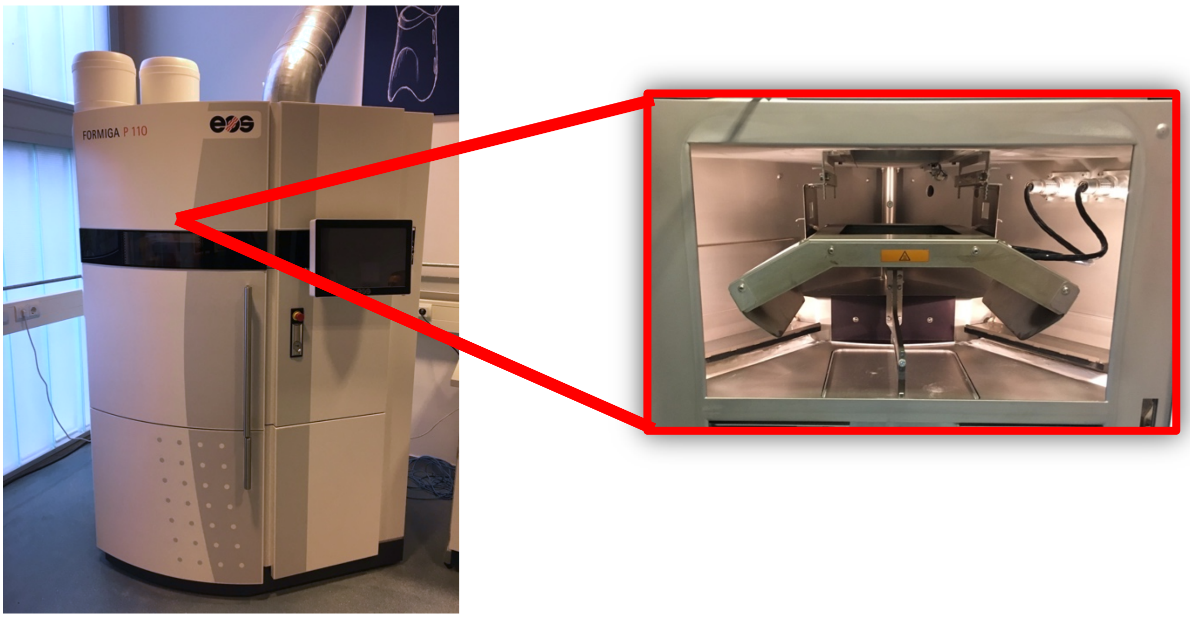



**Fig. 3 – Formiga P110 at UTwente laboratory [Own source]**

### *Stereolithography*

Also known as vat polymerization, it was patented in 1986 by Chuck Hull, founder of 3D Systems. Stereolithography is an additive manufacturing technology that uses photopolymerization to cure layers of liquid resin in a vat where either a Laser point or a projected light is used to harden resin while the support platform of the vat moves downwards/upwards. When the light is sent, there is one layer of liquid between the vat bottom and the last layer of the print. The liquid solidifies and the part is connected both to the build platform and the vat bottom at the same time.

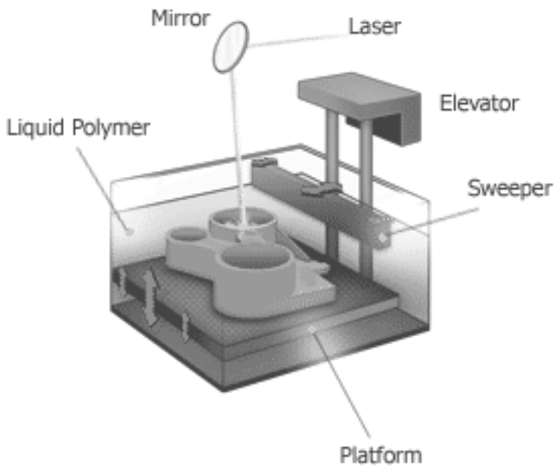



**Fig. 4 - Main components of VATP System**

One of the main benefits of stereolithography is that it can make large parts with very fine details with the lowest surface roughness. However, large parts require a vast amount of liquid resin to fill the vat and a correct UV light isolation system.

It can be used at home or in a professional environment but it has to be remarked than can only be used with specific polymeric materials that have to be correctly recycled.

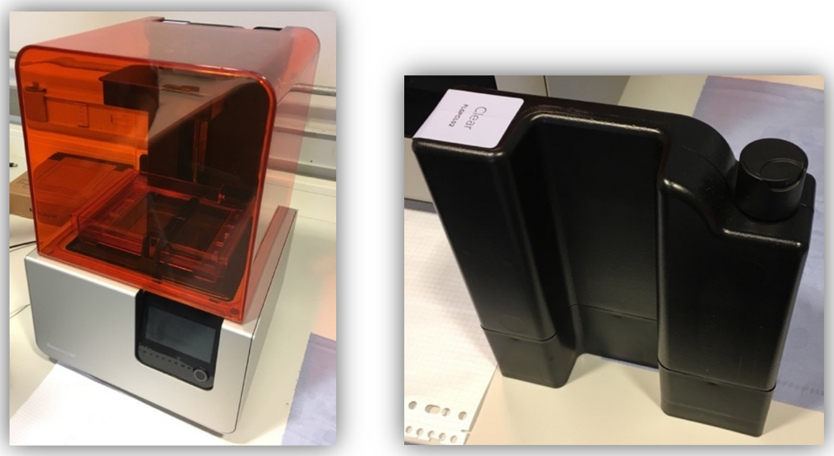



**Fig. 5 - Stereolitography printer at UTwente laboratory and resin container**

### *Binder jetting*

Binder jetting is a relatively young process that is based on adding agglutinant to layers of powder in order to make a solid state bonding.

The binder jetting printers, use a specific mechanism to depose and level the powder for a later adding of binder that conforms the printed parts.

The lack of heat application has benefits and drawbacks: the process is cheap and fast, but the accuracy is not outstanding. However, the lack of heat application leads to a perfect thermal balance in the printed part.

### *Sheet lamination*

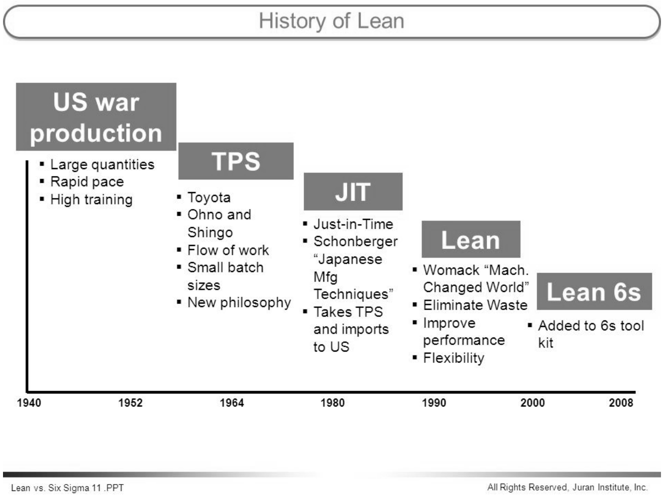
Sheet lamination is also a relatively young process. In standard form SL involves stacking layers of paper/plastic/metal, cuttting by laser and shaping the outer contours of the part, also creating cross hatches for  sections of the layer that has to be removed later.

The applications of sheet lamination are mainly based on the creation of scale models and conceptual prototypes, for the shape or design. It can also be used to make molds for traditional manufacturing, such as sand molds for metal casting processes.

The main disadvantages of Sheet lamination lamination are that the technology does not allow to create pieces as precise as those created by other 3D printing methods, such as stereolithography (SLA) or selective laser sintering (SLS). It is not an ideal technology for the creation of objects with complex geometries and since this process does not produce pieces of very high precision, and it is not usually used to create functional prototypes.

## INTRODUCTION TO LEAN

Lean is a relatively modern production system based on Toyota's Production System after World War 2.




In the middle 1900's, and after witnessing the high impact of Ford in the American market, Japanese engineers decided to adopt the American production and statistical quality techniques. However, Toyota added a simple variant: they changed the conventional vision of employees as workforce and gave them the opportunity to discuss workplace environment and improvements. After giving the employees voice, Toyota developed a set of procedures that ensured the correct production parameters, while reducing time required and changeovers.

### LEAN PHILOSOPHY

Lean is based on a philosophy in which a continuous and systematic analysis of the value chain is carried out, identifying and eliminating activities that do not add value to a process but result in a higher cost or effort. The philosophy is based on a "Everything can be done better" premise, intending to make every company adopt an innovative continuous improvement approach to its own inefficiencies, minimizing the cost, with a competitive quality and with high flexibility.

Customer satisfaction automatically improves, due to the timing and delivery compliance if we base our production on the Lean pillars that conform the philosophy.

Additive Manufacturing in particular is, unlike traditional manufacturing processes, an on-demand technique, which is already a very lean vision of production.

## LEAN VALUE AND WASTE (MUDA), JIT

JIT, or Just In Time is one of the two main pillars of the Lean philosophy: the part should be correct, in the correct series size and delivered in time. It is an industrial sub-philosophy that eliminates every waste of the production chain, from the order to the delivering.

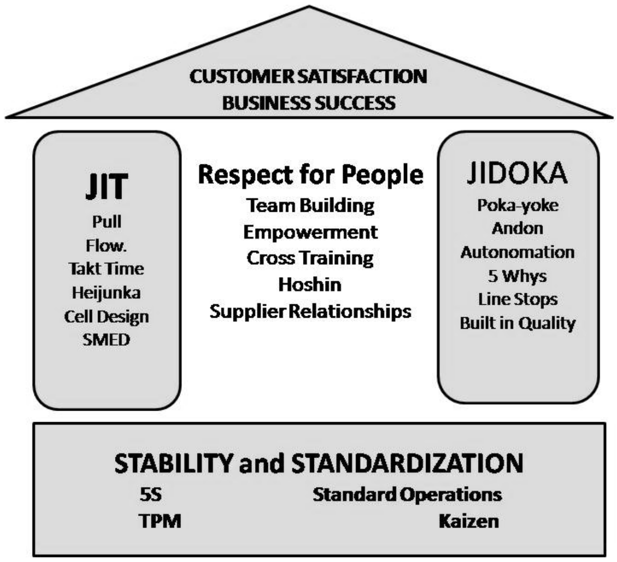



**Fig. 6 - Lean pillars [Source: Lean Institute]**

Lean philosophy evolved from TPS to JIT and to the current Lean/6S philosophy and now understands waste through a very specific definition that commonly leads to industry mistakes. Waste should be understood as "everything different than the minimum resources (materials, machines and workforce) that are needed to add value to a product". In the additive manufacturing case, it seems obvious that the sub-processes that conform and add value to the produced part are not that different from the ones used in traditional manufacturing (i.e. pre-heating the machine chamber or plate instead of the oven, recycling the powder instead of the metal shavings… etc).

This waste has been classified subsequently by different authors and has been summarized into 9 (7+2) types:

1. Over-production
2. Delays
3. Unnecesary movements
4. Unnecesary transport
5. Over-processing
6. Stock
7. Workforce exploitation

8. Environmental wastes

Having defined the waste, the need to talk about the actual value seems crucial. If the previously mentioned activities were the ones that do not add value to the final product, the value is created through processes that result into a physical/chemical transformation of the product for which the client is willing to pay.

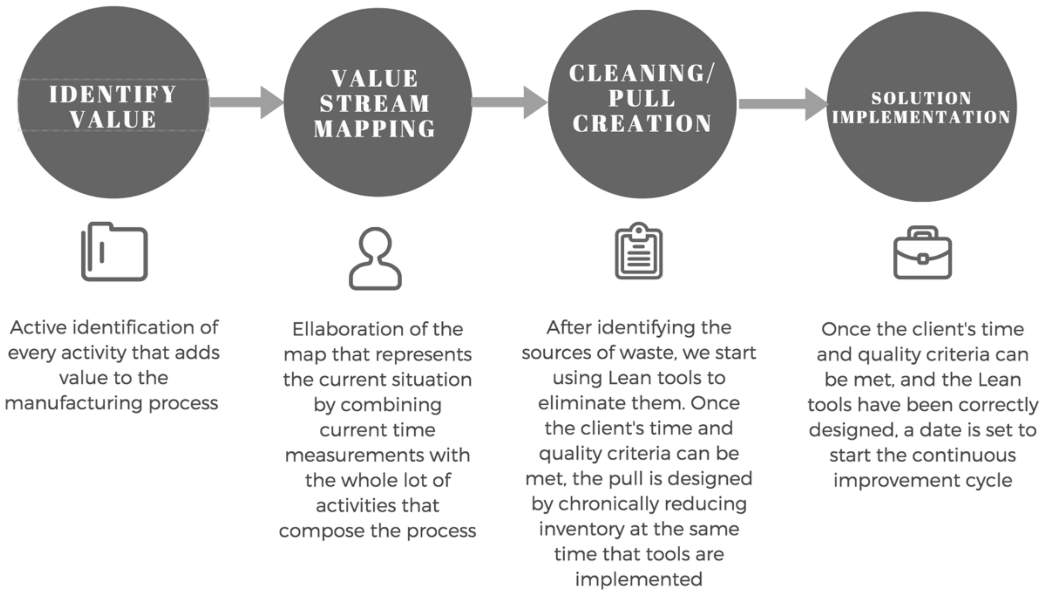



**Fig. 7 – Generic Lean implementation process [Own elaboration]**

Since the mid 20$^{th}$ Century, manufacturers have tried to eradicate the stock excess and to provide a zero-defect service to their clients. The way to do this, is systematizing the process to ensure a constant control, not enabling the supply chain absorb a defective part or wasted times.

The key of systematization is documentation. The traceability is of enormous value to the companies: it allows the chain to reproduce where the fault or defect irrupted, transforming the regular manufacturing process to a whole continuous improvement cycle. The more it's manufactured, the less defect appear (see Kaizen).

| | Action | Tools / Methodologies |
|---|---|---|
| **1st Stage** | Identification of value | Voice of the Customer<br>CTQ Flow Down |
| **2nd Stage** | Value Mapping | Value Stream Mapping |
| **3rd Stage** | Cleaning of processes / Pull creation | SIPOC<br>Fishbone Diagram |
| **4th Stage** | Solution Implementation | * At election of analyst |

**Tab. 1 - Tools along Lean Analysis**

### LEAN AUTOMATIZATION, JIDOKA

Jidōka represents automation with a human touch. In a practical definition, it is a methodology that ensures the quality control at the source of the waste or,in other words, does not allow the defect passing on and on from a process to the following task. This, is relatively innovative, since the traditional manufacturing lines usually inspect the product quality at the end of the product line.

Jidōka means to ensure quality control at the source, is not allowing a defect to pass to the next process, in contrast to the traditional processes that perform inspection at the end of the line, discarding the defective products.

Jidoka consists of:

Andon System: It is the system used to alert of a problem in the production process, generally they are visible and / or audible signals; it refers to a rope that when activated triggers the warning system .

Automatic stops: Devices, sensors, mechanisms, etc. are installed. In the operations that detect any abnormality, they can be applied to processes in which machines or people intervene, in the case of people have the authority to stop the production line or activate the Andon systems, to alert of the problem and to come in their help to solve the root problem (RCA), in summary is

1) Detect the anomaly automatically.

2) Stop the production line.

3) Find the root cause and eliminate it.

Man / Machine Separation: Generally in factories or classic manufacturing processes, the operator takes care of the machines without need while they are doing their job, an example is the operator waiting for a CNC machine to finish its work.

Quality control in the workplace: each worker in the line is responsible for the quality of their work, this prevents defects from happening through the following processes which add costs.

Root cause analysis: Root cause analysis is in itself an effort so that the problem never appears again, the most used method for this analysis is to ask 5 times why ?, in a structured and confirmed each because before passing to the Next, the result of this is the generally hidden reason of the problem and at this moment one can move on to design a Poka-Yoke. This tool will be studied in the following sections.

## LEAN TOOLS

### Lean Value Stream Mapping

Graphical representation of every workflow, activity, material and information in a business that is necessary to design and produce a product and deliver it to the final client.

It is a very powerful and simple tool that serves to graphically represent the current and future state of the production system. All this, with the objective that users have a better understanding of the production phases and the flow of materials. Likewise, it is a key tool that allows us to identify activities that do not add value to our production process.

The steps for the implementation of the Value Chain Mapping are:

1. Selection of a productive critical area
2. Preparation of the map of the current state.
3. Review existing documentation
4. Identification of main processes
5. Define what data is missing and should be collected
6. Collect information

In short, Value Chain Mapping is a very useful tool because it allows analyzing and distinguishing steps and activities that can be improved or eliminated in the production process of a company. The use of VSM allows the organization to have a diagnosis that allows continuous improvement of productivity, and in a sustainable manner.

### 5S/6S

5S is the main tool Lean philosophy uses to transform a conventional manufacturing process to a Lean Manufacturing standard. If the workplace is unorganized, efficiency is consequently reduced, wasted time irrupts and productivity lowers down. 5S is not only applicable to manufacturing; it can also be applied to daily routines at home or, even, in your own car.

This tool is called 5S because it represents 5 principles which, in Japanese, start with these letters. However, due to the current safety regulations in the workplace, a new S was added lately: Security. As it will be stated, every word has a specific meaning to transform the workplace into an optimized, efficient and productive space:

**1 - Seiri (Sort/Classify):** active identification of every material element that is necessary/unnecessary to carry out the daily activity of the worker. For example:

- Malfunctioning tools
- Unnecessary tools
- Papers and documents

Different criteria can be used to define specifically how Seiri can be applied. However, one of the most effective routines is identifying the unnecessary objects with a red card. The operator can place a red tag on tools he doesn´t consider relevant to the manufacturing process. Then, the article is carried to a temporary storage where will be classified either into re-usable or disposable.

**2 - Seiton (Set in order):** everything should be in place when needed. Time is constantly lost when the operator looks for items that are not stored correctly.
One of the main strategies is applying Visual Management to materials by drawing the contour of every tool involved, and situating tools depending on the frequency of usage creating an organised, clean and safe environment that motivates an effective workflow.

Seiton's main benefits are:

- Time and movement economy
- Avoids tool loss
- Ensures the correct usage of tools and elements
- Achieves better aesthetics in the workplace

A good Layout of the laboratory is of crucial importance to ensure a rapid access to every tool needed, to avoid accidents either with the machines or with the material, and to put natural order in the workplace.

When a design or redesign is needed, the 8 Muther factors should be taken in account: Material, Machinery, People, Movement, Wait, Maintenance, Building and Change.

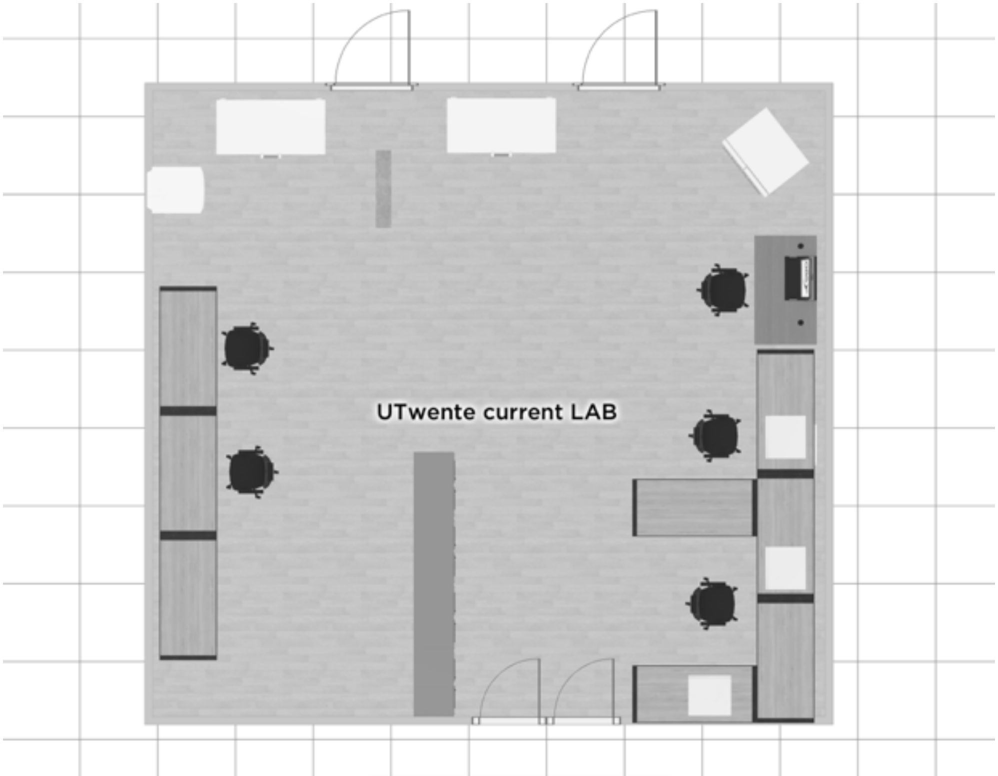



Ilustración 8 - Current UTwente lab layout

**3 - Seiso (Shine/Clean):** The best way to clean is to identify where the dirt comes from. After that, a frequency of cleaning should be imposed to ensure a pleasant and easy-to-use workplace. Cleaning will also become a good way of inspection: oil, air or any substance leaked will be easily identified, reducing the probability of defective manufactured parts.

**4 - Seiketsu (Standardize):** After implementing the first 3 S's we should focus on standardizing the best practices achieved in the work area. Workers should be involved at the time of writing down the standard rules because, at the end of the day, they are the most valuable information sources.

Pictures of the work area in optimal conditions can be placed in order to remind how it should always be.

**5 - Shitsuke (Sustain):** Knowing in advance that this is, probably, the most difficult S to implement, the main difficulty of Shitsuke relies on the human aversion to 'change'. Changing the usual ways of working makes workers go back to the routines rooted in, in many cases, several years. A wide amount of companies implement the first 5S's to see how, in more or less time, the work environment goes back to the usual disorder and dirtiness. In order to avoid this, a strong compromise of the managers must take place by changing the paradigm and designing systems that ensure the continuous improvement.

In the end, the first 5S's should be carried out "without being told".

**6 – Security:** In the recent years, security has been added to the original 5S system in certain industries. Even though it is clear that after implementing the first 5S's, security will grow notoriously, safety should be an independent matter to discuss. Spelling it out as an independent step, gives it greater awareness and focus.

To implement it, potentially hazardous substances and materials should be placed correctly and far from the worker if possible. Security systems such as alarms, water sources to put out fire or correctly dimensioned fume conducts can be a good strategy to ensure a healthy work area.

### Poka-Yoke

Designed by Shigeo Shingo in the 1960's, literally means foolproof. Poka-yoke aims to create an error-free manufacturing process in which, apart from a final quality inspection system, the errors are detected before they become a final defect. By error we mean every aspect done wrongly by the worker.

A Poka-yoke device should inspect the 100% of the produced parts as well as helping a possible corrective process to troubleshoot the potential defect; when this is not possible, a warning system should highlight the defect.

Depending on this two goals we can develop two different Poka-Yoke regulatory functions:

- Control methods
- Warning methods

Control Methods: These methods turn off the machinery, block the system or, if softer action is needed, just tag (physically or electronically) the produced part to prevent final defects. These systems help maximize the efficiency to reach the so desired "zero error" production.

Warning Methods: These methods warn the worker through visual or acoustic information

### SMED (Single-Minute Exchange of Die)

It is the main tool used to shorten the machinery preparation time.

After noticing that the traditional approaches to changing machinery tools were, mainly, focused on training the operators, Shigeo Shingo decided to draw his attention to the efficiency of the tool changing method.

SMED is based on a combination of adjustments aimed to carry out the tool change in less than 10 minutes. We understand by "tool change" every action required after producing the last part of a series until the first product of the following series starts its manufacturing. The time invested during this process is called changing time.

Depending on the nature of these adjustments, they can be classified in:

- Internal adjustments: all of which have to be carried out with the machinery previously stopped.
- External adjustments: they can be carried out during the usual workload of the machine.

The application of SMED systems is especially relevant for companies that manufacture short series (500 parts or less) with a high density of variation (i.e. Additive Manufacturing).

SMED is usually applied after four main stages:

| Stage | Action |
|---|---|
| **Preliminary stage (Stage 0)** | Deep study of the change operation |
| **1st Stage** | Divide between internal/external tasks |
| **2nd Stage** | Transform internal tasks to external |
| **3rd Stage** | Polish both internal and external tasks |

Tab. 2 – SMED Application Stages

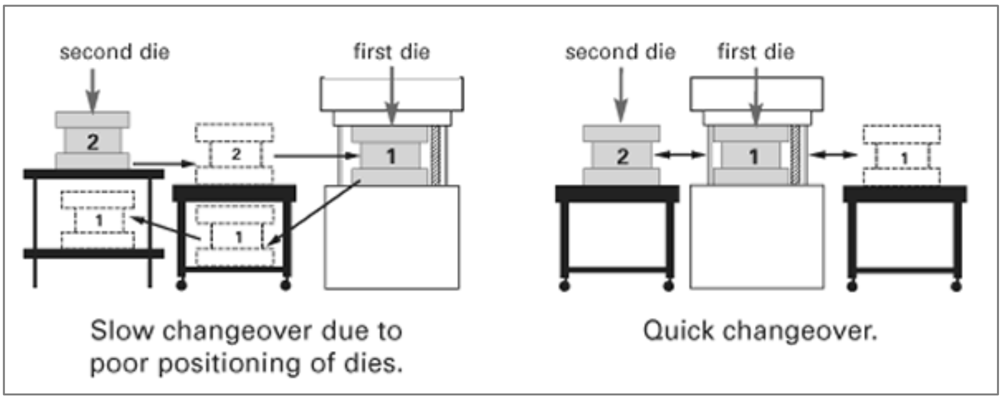



Fig. 9 - Example of Single Minute Exchange of Die [Source: Lean Enterprise Institute]

### Kanban

Kanban, meaning literally "Instruction card", is a highly effective tool that uses cards to help the workers know where they are working at, and under what characteristics.

Originally designed by Toyota in the 50's, Kanban is often combined with Pull Production, and works by assigning a specific card and a container to each manufactured part. These cards contain information about the part (machine reference, part description, next step in the process, etc.) but also states the number of parts that have to fill the container before it moves to the next step. This is a perfect way to ensure that the machines only work when needed and that Pull Production works smoothly.

There are, however, different types of Kanban cards depending on the aim.:

- Production Kanban: Used when set-up time (machine preparation or tool change) is very low or zero. It contains the production order of the component).
- Material Kanban: Situated in specific storage areas, this card works the same way a Production Kanban works. It is a good way to let the supplier know that they have to send new material to the warehouse.
- Urgency Kanban: emitted after a special circumstance (defective manufactured parts, machine failure or extra time) and when the component is urgently needed at some part of the production line.

### Kaizen

The 'Kaizen method' -'Kai 'means' change' while 'Zen' refers to wisdom; so its translation into Spanish could be "continuous improvement" - it has its origin in Japanese culture where the concept that every day must contain in itself the possibility of personal improvement is deeply rooted. Starting from that mental premise, the basis of the Kaizen method is based precisely on the fact that a series of continuous and small improvements is better and more effective than a single large change. We are all afraid of changes and we are intimidated by any challenge that seems large and unreachable (for an additive manufacturing industry, for example, it may be at a certain moment the obligation of having to register incidences in a registration sheet/platform).

The Japanese method tells us that, if we change a huge goal for a small one, by overcoming it, we then initiate that impulse that we need and that will help us reach our final goal over time. It's about improving every day a little until we reach our challenges.

## 1.5 IMPLEMENTATION

### PILOT PROJECT: ADDITIVE MANUFACTURING LAB (UNIVERISTY OF TWENTE)

The University of Twente is proud to constitute the biggest campus in Europe. However, the space optimization is crucial to ensure continuous improvement and adoption of laboratories that develop the most up-to-date technologies.

The Additive Manufacturing Lab works as an independent laboratory that, apart from serving as a research centre, works for external companies in the Overijssel region by serving them with 3D Printed prototypes and, currently, 3D printed final products.

The printing machinery has been operating in the market since 2015, the year in which it began manufacturing operations, to meet the demand of the graphic sector, expanding its market to customers in both the public sector and the private sector. Since then, the activity of the company is focused on carrying out a constant process of the design, manufacturing and distribution process, always seeking the value and satisfaction of the clients and providing service throughout the national territory.

The business model is based on the manufacture of types of parts, which are specific and ranging from the most common to more elaborate and innovative.

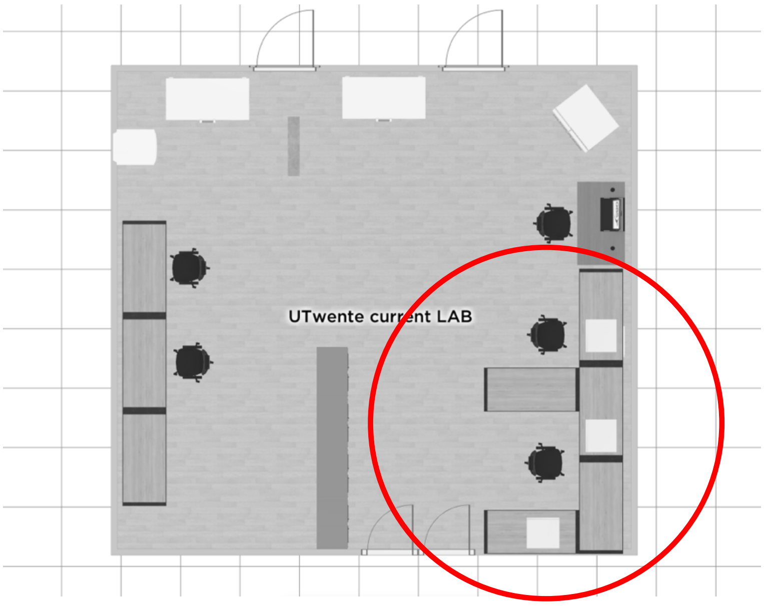



Fig. 10 - Current UTwente 2D layout [Own elaboration]

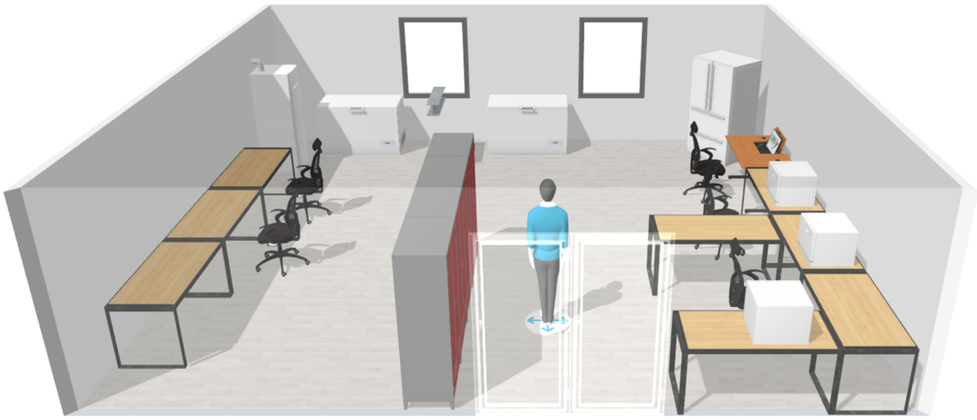


Fig. 11 – Isometric perspective: Current UTwente 3D layout [Own elaboration]

### VALUE IDENTIFICATION (VOICE OF THE CUSTOMER AND CTQ FLOW DOWN)

As it has been stated, Additive manufacturing is a name that covers a wide range of different techniques that are currently applied to various fields (biological printing, printing under extreme conditions…).

The value of Additive manufacturing relies on different aspects that make it a very interesting technique. The 3D Printing value has been deeply studied by various authors that summarize it in the following:

- Time
- Accessibility
- Cost
- Production on-demand

However, and due to the Lean perspective this report tends to acquire, we should focus on the very first step of every Lean implementation: The Voice of the Customer. We understand "customer" by every single one of them that is impacted by the process, either internally or externally.

Due to the limited amount of customers the University of Twente lab has, a phone survey was carried out to identify what aspects the clients value the most and what aspect can be improved. After the result processing the following CTQ Flow Down trees were elaborated:

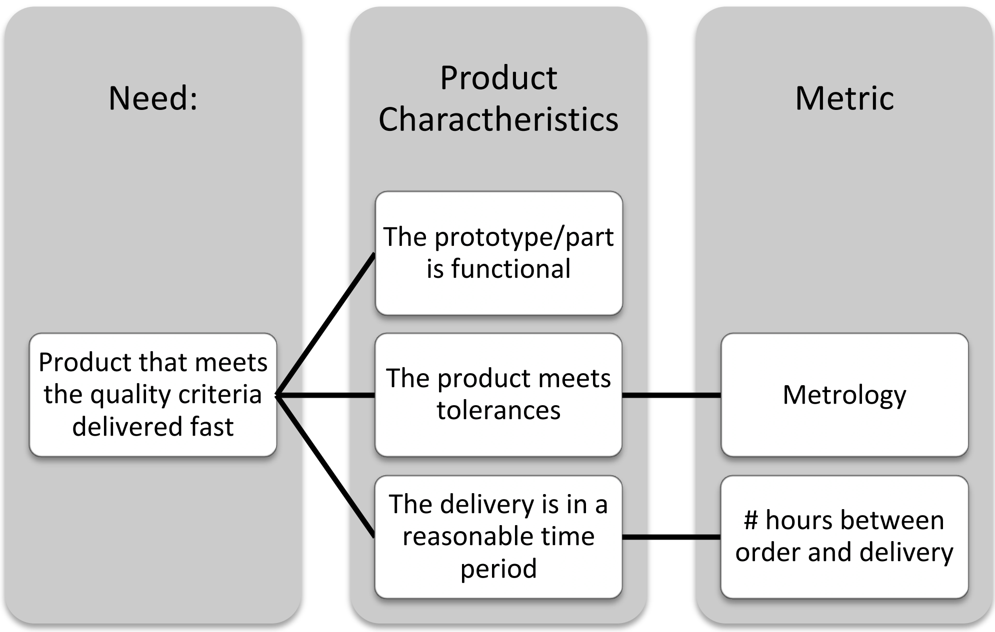



**Fig. 12 - CTQ Flow Down Tree [Own elaboration]**

### PROCESS IDENTIFICATION (TIME MEASUREMENT AND VALUE STREAM MAPPING)

Lean Value Stream Mapping is representing graphically every workflow, activity, material and information in a business, that is necessary to design and produce a product and deliver it to the final client.

As stated, it combines Methods-time measurement (MTM) with the analysis of the whole lot of activities that compose the process.

The most used printers and the ones that will constitute the case of study are the SLS Formiga P110 and the VAT Polymerization printer.

For the creation of the Lean Value Stream Map, the data was gathered on February 2018. The most relevant data for this thesis is apportioned below.

-**Monthly demand**: 26 printed parts and prototypes. Each part or prototype can be printed either through SLS, VAT Polymerization or Material extrusion, depending on the clients' specifications and needs. The part must be finished after through any of the available post-processes (i.e. mechanical polishing, chemical polishing, vibration or thermal stress relief.

- **Daily demand:** Considering 20 labour days, a demand between 1 and 2 parts per day is estimated.

**- Work in process:** accumulation between processes; there is no definition of metrics nor established minimum or maximum times.

-**Delivery term:** the usual delivery term to the final client varies between 3 and 4 days.

**- Available time:** the workday consists of 6 hours per day (rest time not included), that meaning 360 min/day

With the sole purpose of simplifying the thesis, the studied variables correspond to the specific moth of February 2018. This was considered by the workers a “regular month” and so it can be taken as representative.

The most important time measure within the actions of identification for productive processes operations, and that affects the production of the studied group, is the **Cicle Time (C/T**). This time is defined as the necessary to manufacture a product on a uniform regime on the workplace and making it available to pull through the next step in the general process.

We can also define the **batch time** of each process as the sum of the C/T plus the preparation and waiting times.

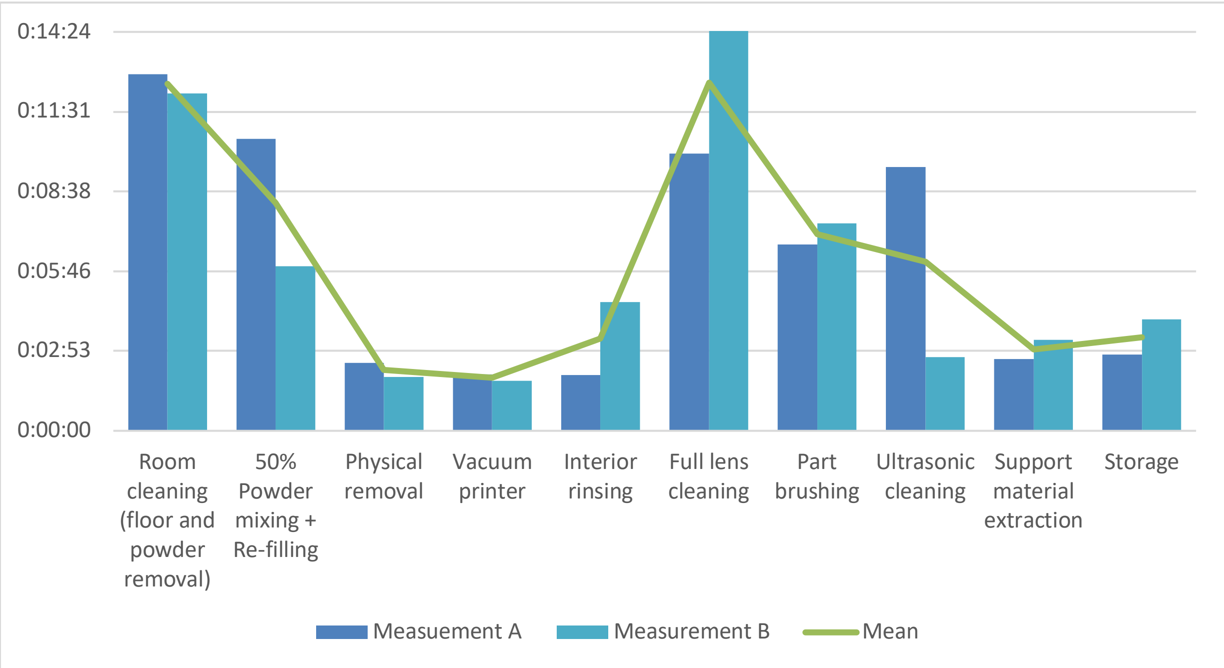
The measured times are the sum of the cicle times and the preparation times or C/O times. The preparation time is made up of derived times of operations as:

- Cleaning machinery
- Material change
- Heating of the machinery
- Transmission and introduction of data into the printers.

Since UTwente LAB offers around 9 types of 3D printing, this thesis considers reasonable to calculate a weighing number (*k*) for every process in order to unify the whole analysis. Therefore, only one Value Stream Map is produced (with the exception of the product cleaning, which is only necessary in powder based processes). Checking the record of the company, approximately 82% of ordered products correspond to SLS Printing, whereas 15% correspond to VAT Polymerization and 3% to other techniques.

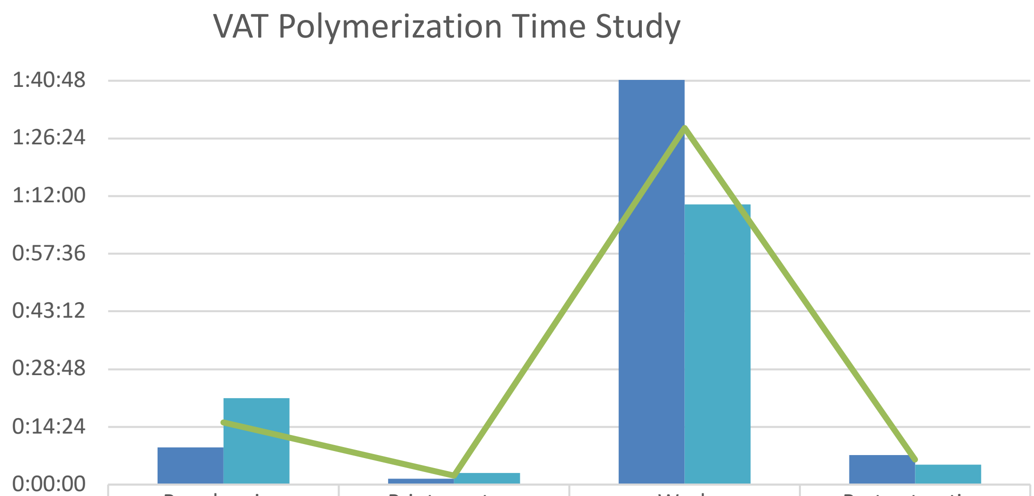
| Process | Sub-process | Measure. A | Measure. B | Mean |
|---|---|---|---|---|
| **Pre-cleaning** | Room cleaning (floor and powder removal) | 0:12:11 | 0:12:53 | 0:12:32 |
| **Printer set up** | 50% Powder mixing + Re-filling | 0:05:56 | 0:10:32 | 0:08:14 |
| | Pre-Heating | 2:20:00 | 1:58:00 | 2:09:00 |
| **Part extraction** | Physical removal | 0:01:57 | 0:02:27 | 0:02:12 |
| **Printer cleaning** | Vacuum printer | 0:01:48 | 0:02:02 | 0:01:55 |
| | Interior rinsing | 0:04:39 | 0:02:01 | 0:03:20 |
| | Full lens cleaning | 0:10:01 | 0:12:34 | 0:15:07 |
| **Cleaning and storage of the printed product** | Part brushing | 0:07:29 | 0:06:43 | 0:07:06 |
| | Ultrasonic cleaning | 0:02:40 | 0:09:32 | 0:06:06 |
| | Support material extraction | 0:03:17 | 0:02:35 | 0:02:56 |
| | Storage | 0:04:01 | 0:02:45 | 0:03:23 |
| | | 2:59:31 | 3:09:18 | 3:19:05 |

Tab. 3 - SLS Printer time measurements of sub-processes except actual printing



| Process | Sub-process | Measured time A | Measured time B | Mean |
|---|---|---|---|---|
| **Pre-cleaning** | Machinery cleaning (resin) | 0:09:20 | 0:21:34 | 0:15:27 |
| **Printer set up** | Resin re-filling | 0:01:30 | 0:02:58 | 0:02:14 |
| **Work** | WIP | 1:48:00 | 1:10:00 | 1:29:00 |
| **Part extraction** | Physical removal | 0:07:22 | 0:05:02 | 0:06:12 |
| **TOTAL** | | 2:08:02 | 1:39:34 | 1:53:48 |

Tab. 4 - VAT Printer time measurements




| | Pre-cleaning | Printer set up | Work | Part extraction |
|---|---|---|---|---|
| Measuement A | 0:09:20 | 0:01:30 | 1:48:00 | 0:07:22 |
| Measurement B | 0:21:34 | 0:02:58 | 1:10:00 | 0:05:02 |
| Mean | 0:15:27 | 0:02:14 | 1:29:00 | 0:06:12 |

## Environmental correction for the time study

| | | | |
|---|---|---|---|
| | ***GENDER*** | ■ MAN | □ WOMAN |
| **Constant supplement** | **Personal needs** | 5 | 0 |
| | **Fatigue based** | 4 | 0 |
| | ***Is work carried out standing?*** | SOMETIMES | |
| | | 0 | |
| ***Abnormal stance*** | ***How comfortable is the regular stance to carry out the job?*** | Slightly uncomfortable | |
| | | 0 | |
| ***Strength usage*** | ***Pulls, throws or pushes a weight equivalent to:*** | 1 Kg | |
| | | 1 | |
| ***Lights*** | ***Light perception is:*** | Sdightly under regular interior light | |
| | | 0 | |
| ***Visual stress*** | ***The operation requires:*** | Some precision | |
| | | 0 | |
| ***Noise*** | ***The perceived noise sensation is:*** | Strong and intermitent | |
| | | 2 | |
| ***Mental stress*** | ***The carried out operation is:*** | Complex / Divided atention | |
| | | 4 | |
| ***Monotony*** | ***The carried out operation is:*** | Slightly monotone | |
| | | 0 | |
| ***Physical monotony*** | ***The carried out operation is:*** | Boring | |
| | | 2 | |
| ***TOTAL CORRECTION*** | | | |
| | | 17% | |

Tab. 5 - Time study environmental correction [Own elaboration]

**Calculation of Adjusted C/T's:**

$$C/T_{cleaning\ machinery} = C_f * \left[0{,}83 \cdot \left(t_{vacuum} + t_{rinsing} + t_{lens} + t_{SetUp}\right) + 0.17 \cdot \left(t_{resin} + t_{re-filling}\right)\right] = 1309\ s = 21 \min 49\ s$$

$$C/T_{CAD\ Adjustments} = C_f * [0{,}83 \cdot (t_{CAD\ SLS}) + 0.17 \cdot (t_{CAD\ VAT})] = 13 \min 01\ s$$

$$C/T_{fabrication} = C_f * [0{,}83 \cdot (t_{SLS\ WIP}) + 0.17 \cdot (t_{VAT\ WIP})] = 12h\ 03m$$

$$C/T_{product\ cleaning} = C_f * \left[0{,}83 \cdot \left(t_{support\ removal} + t_{part\ brushing} + t_{ultrasonic\ cleaning} + t_{storage}\right) + 0.17 \cdot \left(t_{physical\ removal}\right)\right] = 26\ min$$

Actual readings of C/O:

$$C/O_{cleaning\ machinery} = 59 \min 21\ s$$

$$C/O_{CAD\ Adjustments} = 3\ min$$

$$C/O_{fabrication} = 21\ min$$

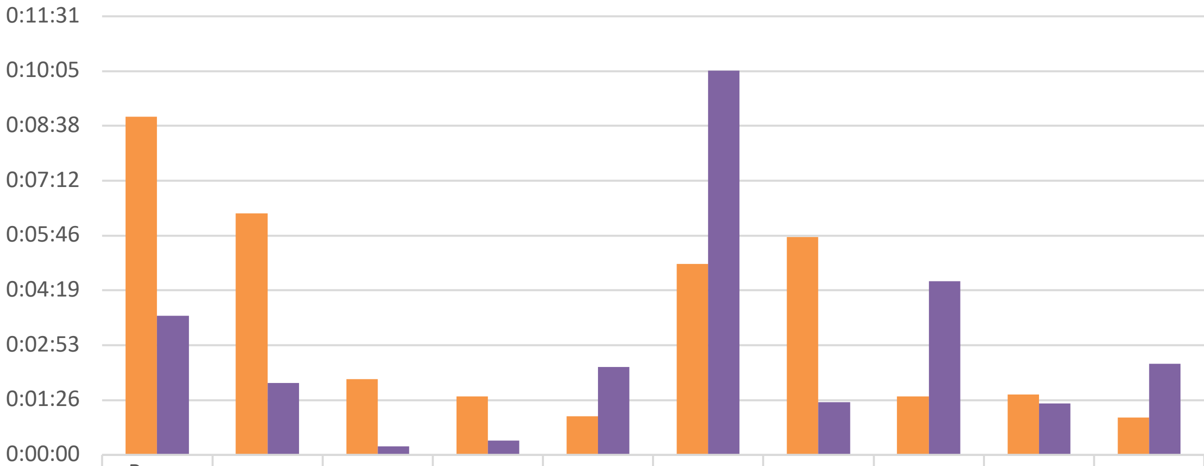
$$C/O_{product\ cleaning} = 0\ min$$

Once the cycle times and C/O times of the products and families of objects of study have been studied it is necessary to make an analysis of the real production times of the manufacturing orders in order to know the times in which there are no contributions of value in each one of the processes.

## Value added vs. OBSERVED Non-aggregated value in production orders

Adding a little bit of perspective on the previous results, it seems of special relevance the high time that does not add value to the process, on average 40%, during the printing of products, taking into account the results of the Value Stream Mapping, which reflects that process Printing is the bottleneck of the system.

In order to know in detail the causes of the high time that does not add value to the process, first of all, a study of it will be presented with the purpose that from it, solutions that contribute to eliminate this bottleneck can be incurred.




| | Room cleaning (floor and powder removal) | 50% Powder mixing + Re-filling | Physical removal | Vacuum printer | Interior rinsing | Full lens cleaning | Part brushing | Ultrasonic cleaning | Support material extraction | Storage |
|---|---|---|---|---|---|---|---|---|---|---|
| Value added | 0:08:53 | 0:06:21 | 0:01:59 | 0:01:32 | 0:01:01 | 0:05:01 | 0:05:43 | 0:01:32 | 0:01:35 | 0:00:59 |
| Non-aggregated time | 0:03:39 | 0:01:53 | 0:00:13 | 0:00:23 | 0:02:19 | 0:10:06 | 0:01:23 | 0:04:34 | 0:01:21 | 0:02:24 |

**Fig. 13 -Comparative between value added and non-aggregated value in SLS printing**

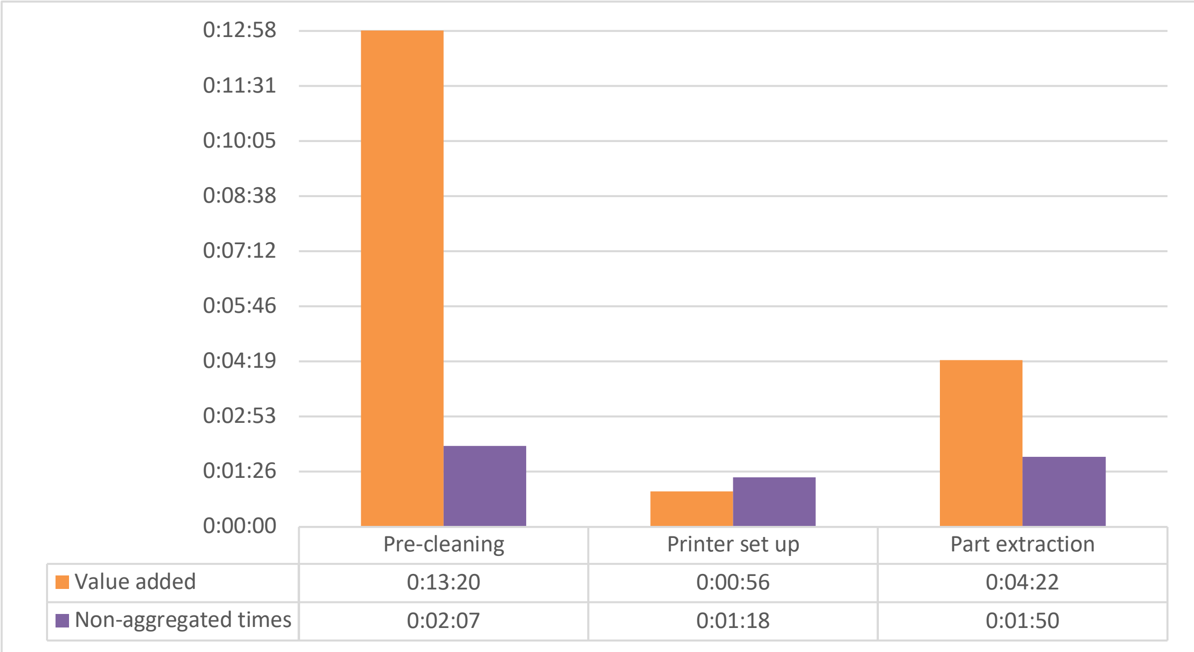



Fig. 14 - Value added vs. Non-aggregated times VATP

## ADDITIVE MANUFACTURING LAB - VALUE STREAM MAPPING

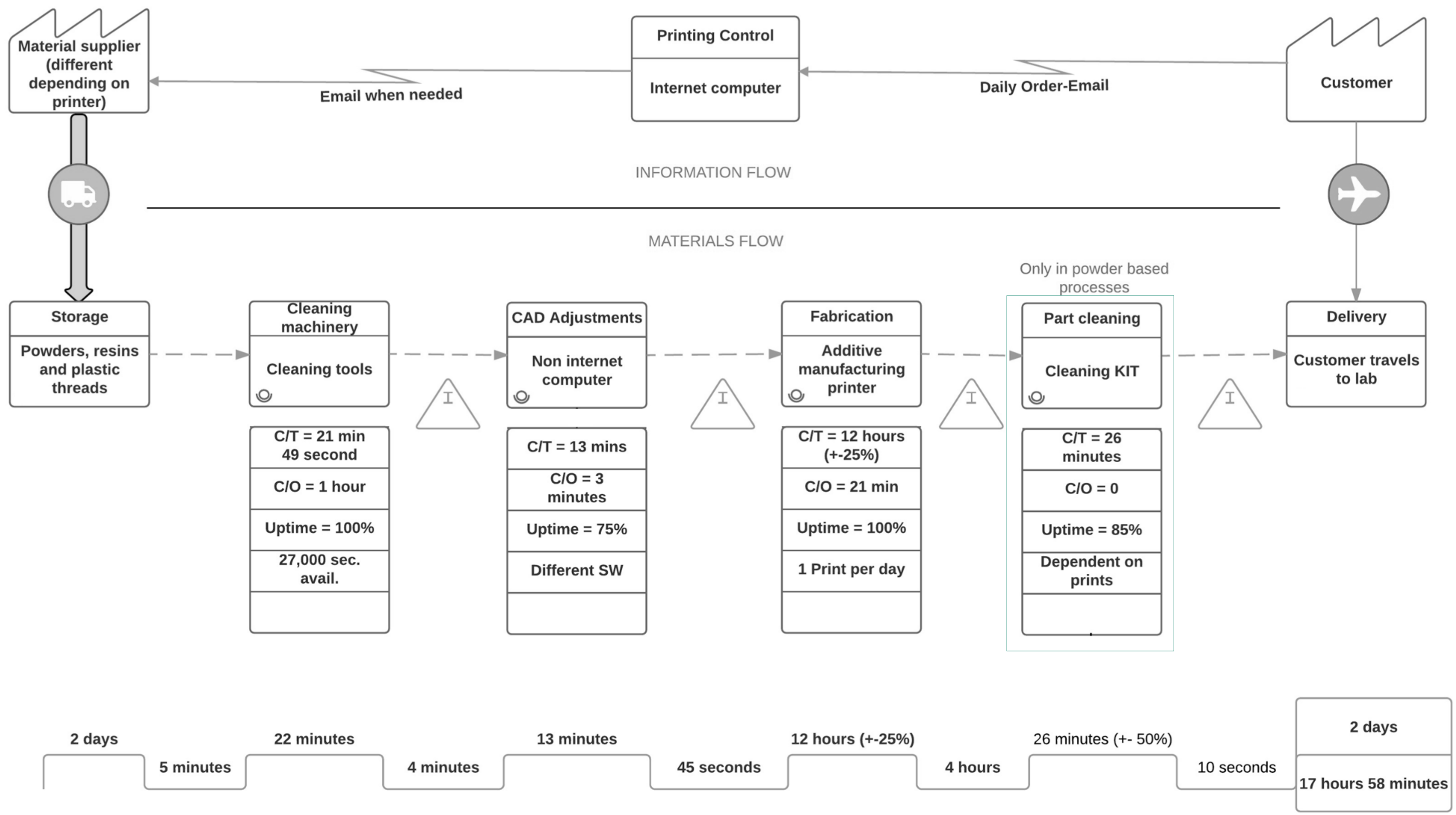



Fig. 15 - Current Value Stream Map [Own elaboration]

## CLEANING THE PROCESS

### SOURCES OF WASTE (SIPOC ANALYSIS AND FISHBONE DIAGRAM)

As described above, the transition to a Lean Manufacturing approach requires technological and human resources along with management conditions. Due to the multiple techniques and diversity possible in the implementation of this management model, it is necessary to be very clear about the current status of FQM, for which everything learned during the work in the plant and the analysis of data that will be taken into account will be taken into account. have been shaped throughout this work.

According to the approach, among the main conditions are an organization, cleanliness and order to which the technique of the 6S is the basis for an efficient application, in addition to which a standardization is necessary as a basis for the application of Lean techniques. . On the other hand, and as discussed in section 6.2 above, the problems detected in the company are two:

- High values in the times of changes and preparation. To do this, the SMED technique will be used

- Incidents and breakdowns. These incidents mainly and as it has been developed in the previous section are:

- Breakage of the part.
- Stains
- Color tones.
- Problems with electronics.
- Problems with warping.
- Incidents with variable printing equipment.

For this, the TPM and Poka Yoke techniques will be applied fundamentally.

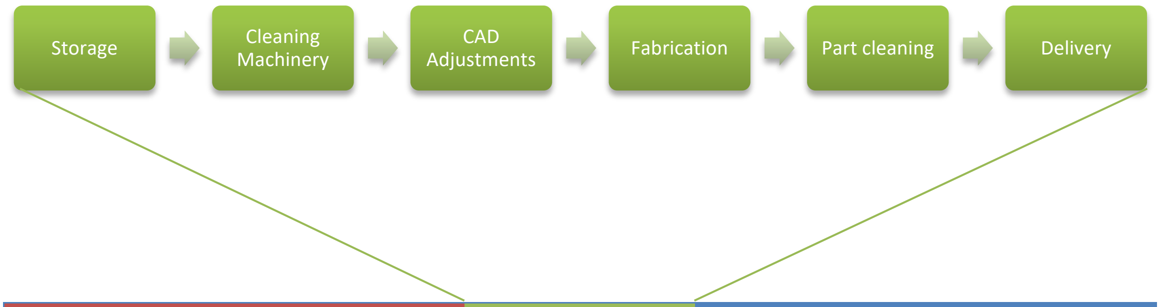
Focusing on the case of FQM, an observation process was carried out at the plant to verify the way in which the raw materials necessary for the processes were arranged, the cleaning of the machines and in general the organization of the work areas of the operators. . The results are that in this case, the head of production of the company has done an important job of awareness and discipline to its operators in these aspects. The materials, tools and raw materials are placed in a position of easy access to the operators and each of them is responsible for the cleanliness of their position.

SIPOC (also called COPIS) is a high level flow diagram which will allow us to visualize the sequential steps of the 3D Printing process by defining the inputs, outputs, suppliers and clients. Its main virtues are that, with it, it is possible to specify the scope of the Lean 6 Sigma projects, clarify the roles of the parties involved and, especially, it is very useful to identify the clients.

It allows to have a consistent knowledge of the analyzed process since it is agreed by the team of the improvement project. The procedure to carry out a SIPOC is very simple: it involves listing the parties involved in the project, distinguishing between Suppliers (Suppliers), Inputs, Process, Output and Clients.

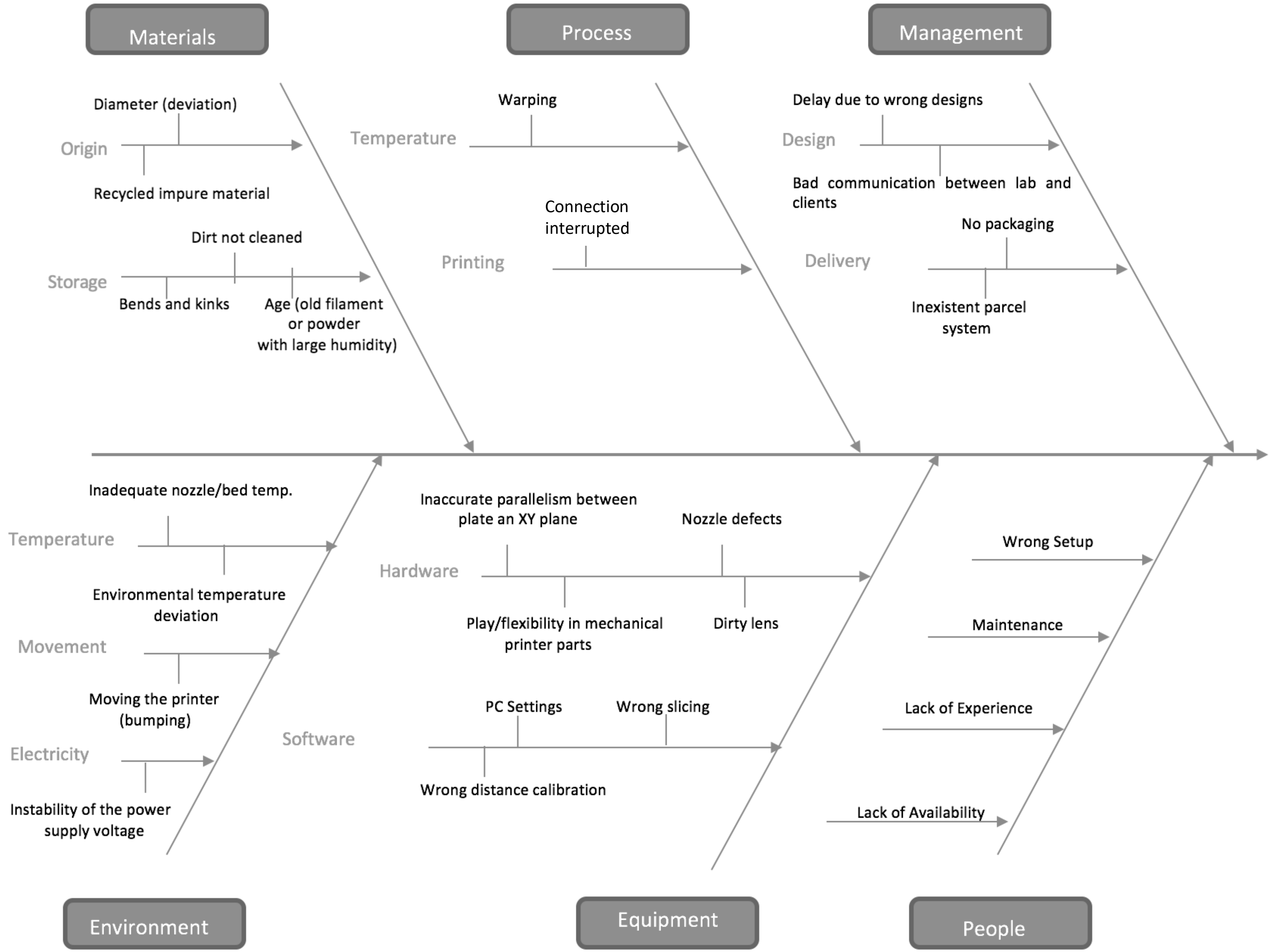
With the SIPOC created, you can see which activities are involved and how they are interconnected. In addition, the parties involved can easily be discerned from those that are not. Finally, it helps to identify the clients and highlight those that have to be satisfied according to the objectives of the project.

After defining the Lean Value Stream Map of the process carried out in the Additive Manufacturing Laboratory, we can zoom out and fit the general process diagram into the SIPOC.




| Suppliers | Input | Process | Output | Customer |
|---|---|---|---|---|
| Raw material suppliers | VAT Resin<br>Powder<br>Polymere thread | Storage | | |
| 3D Printer company (Cleaning supplies) | Cleaning toolkit | Cleaning machinery | | |
| Final client | CAD File | CAD Adjustments | .stl File<br>.obj File | |
| Electricity supplier | Electricity<br>Raw Material | Fabrication | Raw manufactured part | |
| | | Part cleaning* | Clean part | |
| | | Delivery | | Final customer |

Fig. 16 - SIPOC Diagram [Own elaboration]



Materials
Process
Management
Diameter (deviation)
Origin
Recycled impure material
Dirt not cleaned
Storage
Bends and kinks
Age (old filament or powder with large humidity)
Warping
Temperature
Connection interrupted
Printing
Delay due to wrong designs
Design
Bad communication between lab and clients
No packaging
Delivery
Inexistent parcel system
Inadequate nozzle/bed temp.
Temperature
Environmental temperature deviation
Movement
Moving the printer (bumping)
Electricity
Instability of the power supply voltage
Inaccurate parallelism between plate an XY plane
Nozzle defects
Hardware
Play/flexibility in mechanical printer parts
Dirty lens
PC Settings
Wrong slicing
Software
Wrong distance calibration
Wrong Setup
Maintenance
Lack of Experience
Lack of Availability
Environment
Equipment
People

## WASTE REDUCTION (DMAIC)

DMAIC is a Lean methodology that was created by Bill Smith (Motorola) in 1994 and aims to optimize processes in an iterative way. DMAIC stands for Define, Measure, Analyze, Improve and Control.

For the "Define" phase, we should have already identified the problems, and is exactly what we did by elaborating the Fishbone Diagram in the previous section.

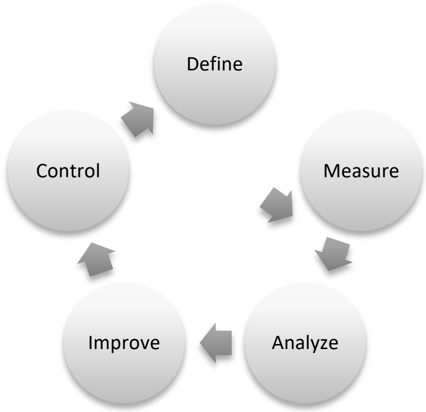



**Fig. 17 - DMAIC stream [Own elaboration]**

After defining where the problems come from, we must stablish a "Metrics" system by measuring parameters that help us on the identification and troubleshooting. In our case, metrics and its analysis have been fused into one simple identification, white definition is segmented by the inefficiency groups defined previously in the Ishikawa diagram and Control and improvement is analysed separately.

*Due to the specifity of the *warping* problem, it seems reasonable to illustrate the reader with a graphic representation of warped defective parts taken at UTwente:

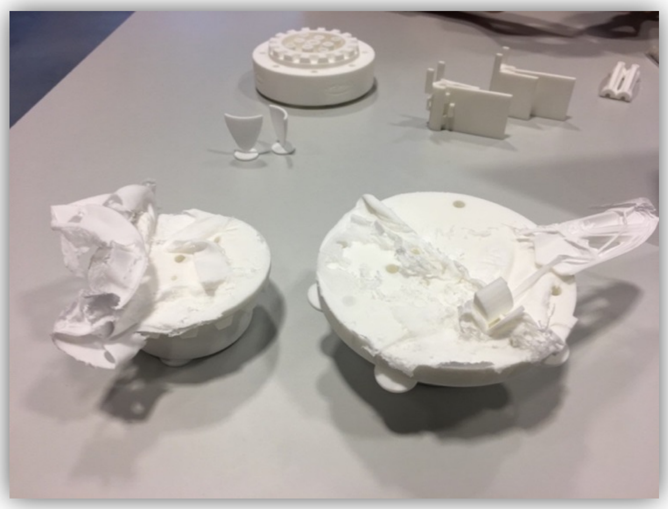


**Fig. 18 - Warped defecetive parts [Own source]**

On the following table we can see each identified problem and the corresponding metric and material that should be used in the Additive Manufacturing Lab at the Univeristy of Twente:

| | Wasted time/cost(quality due to: | Indicators and Analysis | Acceptable value/interval | Maximum superior deviation | Minimum inferior deviation | Material needed to improve |
|---|---|---|---|---|---|---|
| MATERIALS | Deviation in Diameter (Supplier) | Geometrical measurement of the incoming material | +- 0,01mm within declared measurement | +0,015mm | -0,015 | Calibre tool |
| | Recycled impure material (Supplier) | % of purity | 50% | Until 100% | | Material analysis at laboratory entrance |
| | Bends and kinks (Storage) | Number of material damages | 0 | 2 | | Cushioning surrounding machinery |
| | Dirt (Storage) | Hours/week dedicated to clean storage | 2,5 | 2,5 | 1 | Industrial vacuum cleaner |
| | Age of raw material (Storage) | Current date - date of supply | 3 months | 2 months | | |
| ENVIRONMENT | Inadequate nozzle temperature | | | | | - |
| | Environmental tem. deviation | Room temperature | 23ºC | 5ºC | 5ºC | Smart thermostat |
| | Bumping the printer | Number and date of printer bumps | 0 | 1 | | Printer bumps registration sheet |
| | Instability of the power supply | Number of electricity cuts per year | 2 | 1 | 2 | SAI |

| | | | | | | |
|---|---|---|---|---|---|---|
| PROCESS | Warping* | % warped parts/produced parts | 5% | 7% | 0% | |
| EQUIPMENT | Parallelism of the plate | - | +- 0,5º | +0,1 | -0,1 | |
| | Nozzle deffects | Number of defective parts due to nozzle deffect | 0 | 1 | 0 | Nozzle maintenance |
| | Dirty lens (only PBF) | Minutes dedicated to lens cleaning | 30 minutes per day | 45 minutes per day | 20 minutes per day | Lens clening ki |
| | Play in mechanical printer parts | - | | | | |
| | PC Settings | Number of help requests to IT | 0 | 2 per month | | IT Support |
| | Wrong slicing | Number of re-slicing processes per part | 0 | 1 | | |
| | Wrong distance calibration | Number of defective parts due to wrong distance calib. | 0 | 1 per 6 months | | |
| MANAGEMENT | Delay due to wrong designs | Number of complaints from the operator to the client | 0 | 2 per year | | |
| | Bad communication between lab and clients | Number of complaints from the client to the operator | 0 | 1 per semester | | |
| | Unexisting packaging | - | | | | |
| | Unexisting parcel delivery system | % Number of delivered parts / number of produced parts | 90% | 100% | 50% | Parcel company contract |

| | | | | | | |
|---|---|---|---|---|---|---|
| PEOPLE | Wrong setup | Monthly mystery check of the setup by the manager of the laboratory | | | | |
| | Wrong Maintenance | Yearly maintenance | | | | • Machinery warranty<br>• Maintenance calendar |
| | Lack of experience | Hours of worforce training per year | 60 | 55 | 100 | Workforce training |
| | Lack of availability | Productive hours per day | 8 | 9 | 7 | Entrance control |

**Tab. 6 - Metrics for specific waste sources in additive manufacturing [Own elaboration]**

After the elaboration of problems and solutions table, which is an angular stone of this thesis, it is time to choose some of the Lean tools defined in the previous sections.

Due to the Additive manufacturing laboratories' disposition, economical structure and human/material resources, the following tools were chosen to best troubleshoot the problems the UTwente laboratory is currently facing:

### TPM – Total Productive Maintenance

It is a set of techniques destined to eliminate breakdowns through the collaboration of workers. With this it is possible to improve the efficiency of the equipment, improve the production and involve the personnel.

Product processes have losses due to:

• Dead times: breakdowns, preparation, adjustments, material finding.

• Defects: repetition of jobs, less performance in the start-up ...

• Empty times.

As has been done previously, one of the main problems of UTwente is the delays due to these three previous points, and the failures due to wrong designs or unadequate environmental conditions, problems by warping, repetitions due to color defects, problems are punctual but existent. In addition, on many occasions it has been observed in the laboratory, that the operations are carried out repeatedly since they do not work well the first time, which is a problem derived from the fact that, as mentioned, the operations, with the exception of printing, are totally manual. For all this it is essential that the maintenance in this laboratory is key for all.

• Step 1: motivation of the staff and seek their commitment. In addition, the necessary training must be given to them for the application of maintenance. In case of UTwente the machinists are not experts due to the lack of experience, so their knowledge of the operation of the machines is limited.

• Step 2: the operator is given the ability to act freely in the maintenance of the equipment. Standard, standardized checks should be performed and written records should be recorded. An example could be the one shown below, where "type of maintenance" refers to operations that the production manager must standardize for each type of machine in relation to what is considered appropriate.

• By agreement with the lab management, a corrective maintenance of 3 hours per year is considered reasonable and sufficient, which is 540 minutes. This maintenance is intended to achieve a reduction in insulation times.

### Poka Yoke

As it was stated, Poka Yoke is a process used to prevent, and detect errors in the system, also known as "zero defects". Therefore, the objective will be to increase customer satisfaction by avoiding or decreasing errors.

It is a procedure based entirely on inspection, which consists in finding a defect once, stopping the process and investigating the possible causes and possible future causes as well. This purpose can be achieved in different ways:

• Using devices to detect errors during the process.

• By designing products that are “assembler friendly”.

• Using devices that prevent products that have been left from the process from being manufactured with defects.

The electrical faults and machinery must be solved by applying a regular maintenance as described in the previous section to try to maintain the state of the equipment in the best possible condition and, thus, avoid possible breakdowns.

Therefore, once the errors and their possible causes are identified, Poka Yoke will be implemented to avoid some of them:

- Elimination of errors due to raw material wrong selection.

- Platform to detect design errors between laboratory and client

- Inspection of the diameters of the extrusion coils.

- Inspection of the purity of the powder (in powder bed fusion processes).

- Send a signal when room temperature is inadequate

- Elimination of interferences caused by dust and vibrations.

- Analogue and discrete outputs.

The objective of incorporating these devices has two main objectives:

- Avoid defective 3D printing:

Real time image comparison should be used to avoid that a coil with some type of error in format, color, veil, stains... is produced and the operator does not know until the complete printing of the same, since the work will have to be repeated and this involves time, material and financial costs.

- Avoid constant supervision of operators:

Through these sensors it is possible to avoid that the operator has to constantly monitor the printing, since the production of a lot can last hours, in which the operator does not perform any activity except to monitor that everything works correctly. With the incorporation of the sensors the operator has free access to be able to carry out exchange operations in parallel with another operator in another machine, with the aim of reducing the changeover times.

These sensors should be connected to a control system, a PC, which will be responsible for general alarm.

Also, and for this section, a filament type classifier was chosen to avoid problems of color and diameter.

| | | | |
|---|---|---|---|
| **PROBLEM REGISTRATION SHEET** | | | SHEET |
| **STATE:** | | **COD:** | |
| **DATE** | **RESPONSIBLE** | **CAUSE** | **NOTES** |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

**Fig. 19 – Designed Problem registration sheet**

### Kaizen

This lean technique consists in documenting standards, activities and methods to provide continuous improvement. It is the starting point to obtain opportunities for improvement, for which, as is obvious, the participation of workers who carry out and participate in them is vital.

It is intended with this tool to establish a way of working for all the workers to follow it, in such a way that they all carry out the activities in the same way and in the same sequence.

As we have already seen, in UTwente, the Takt Time of the process is less than the Time Tact of each one of the families studied, however, the delivery times are not often reached. This technique presents a review of the activities and procedures that may improve the times. Operators work methods improve productivity, reduce the risk of errors, establish a documentary basis of the processes that can be the source of future improvements and can be the cause of the detection of waste and defects.

The application of standardized work is done in several steps:

1. Establish and select the activities in the process.

2. Carry out the measurements in terms of time of the activities and operations required.

3. Document the optimized sequence of capacity.

4. Define the standard sequence of operations

5. Document and train the established methods.

As an additional material, a problem registration sheet should be implemented and used to ensure that problems are registered and fixed:

Everything related to the design of the workstation has been developed taking into account several ergonomics criteria,as well as with the intention that with the new arrangement of materials and tools, the manufacturing becomes easier and more intuitive. In this way, it will be easier for the worker to memorize and systematize the process, thus avoiding failures and losses of time that do not add value to the product.

We can obtain a general view of the workstation in the following illustrations:

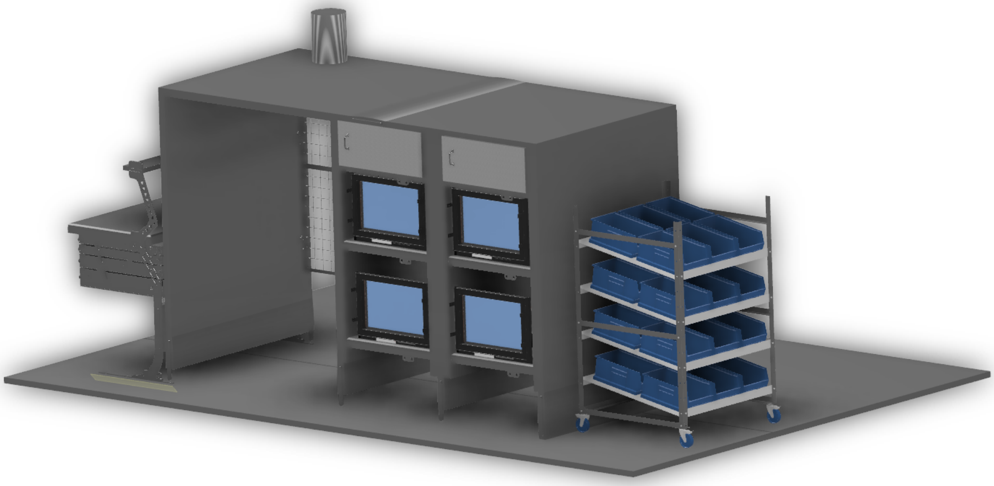


**Fig. 20 - Front design printing station**

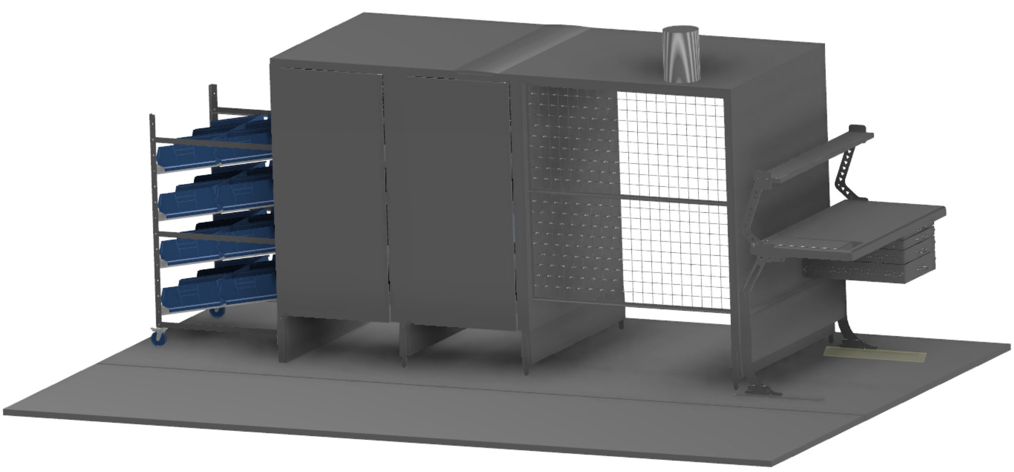
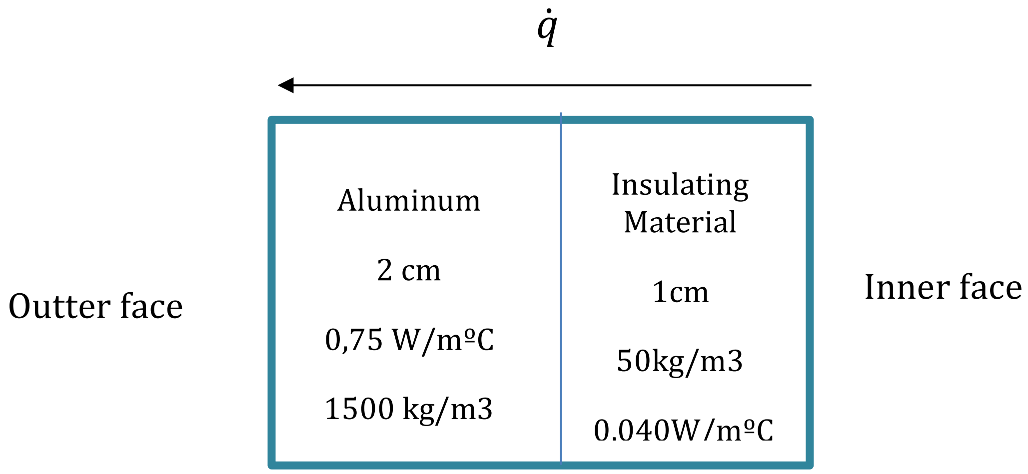


**Fig. 21 - Rear design printing station**

## TEMPERATURE ISOLATION

To calculate temperatures on each face of the workstation,




Being the external temperature the most extreme edge (-2.5ºC), the optimal working temperature of the machines (22ºC) and the resistances corresponding to each wall section, the total heat flow through the wall can be obtained .

$$q = \frac{\Delta \mathrm{T}}{\mathrm{Rtot}} = \frac{Text - Tint}{\mathrm{Rtot}}$$

Knowing that it is constant along the different sections of the wall, we can find the temperature at the different points.

R=1,88 $W/m^2K$

$$\ddot{q} = \frac{T_{int} - T_{ext}}{R_T} = 12{,}128 W/m^2$$

$$12{,}128 = \frac{T_1 - T_{ext}}{R_{se}} \rightarrow \boldsymbol{T_1 = -2{,}015\ ºC}$$

$$12{,}128 = \frac{T_2 - T_{ext}}{R_{se} + \frac{0{,}3}{0{,}75}} \rightarrow \boldsymbol{T_2 = 2{,}84\ ºC}$$

$$12{,}128 = \frac{T_3 - T_{ext}}{R_{se} + \frac{0{,}3}{0{,}75} + \frac{0{,}05}{0{,}04}} \rightarrow \boldsymbol{T_3 = 18\ ºC}$$

### GLASS DOORS

Now the heat losses that occur through the windows are calculated by performing the following calculations:

$$\ddot{q} = \frac{T_{int} - T_{ext}}{R_T} = 57{,}511\ W/m^2$$

$$57{,}511 = \frac{T_{int} - T_{int\ vent}}{R_{si}} \rightarrow \boldsymbol{T_{int\ vent} = 14{,}52ºC}$$

$$57{,}511 = \frac{T_{ext\ vent} - T_{ext}}{R_{se}} \rightarrow \boldsymbol{T_{ext\ vent} = -0{,}2ºC}$$

$$Q_{gen} = Q_{SLS} + Q_{VAT} + Q_{extrusion} - Q_{walls} - Q_{glassdoors} = 3{,}13\ kW$$

Specifying the value of the flow that must be provided by the Air Treatment Unit (hereinafter, AHU) as 2000.0 m3 / h and the values of sensible and latent load we have to choose a AHU that adjusts to the needs.

After investigating the main offers of the current manufacturers, it was decided to choose the model 39CQ of Carrier © company in its variant Ceiling-Mounted with lower access. Said unit, in addition to complying with the cooling / heating specifications, is optimal to be installed in the false ceiling of the landing access to the installation space, having a height not exceeding 400mm and being ultra-modular type. In addition, it has a soundproofing system to avoid disturbing noises in the environment and, according to the manufacturer, is especially suitable for offices and work spaces.


Fig. 22 - AHU Carrier

The flow limitation of the unit is 2000 $m^3$ / h and the power of 15kW in sub-model 025; values that comply with the work margin of the machines.

| 39CQ | | 025 | 040 | | 060 |
|---|---|---|---|---|---|
| Assembly | | Ceiling-mounted (C), Floor-mounted (F), Vertical (V) | | | |
| Width/Height | | 750*400 | 1310*400 | | 1880*400 |
| Nominal air flow (m3/h) (Speed: 3.1 m/s across finned layer) | | 2000 | 4000 | | 6000 |
| "Asynchronous motor NPL technology" | Plug fan | 1 | 1 | 2 | 2 |
| | Electric motor | 1 | 1 | 2 | 2 |
| | Available power | 0.55 kW | 4-pole/1.1 kW - 2-pole/1.4 kW | | - 2 pole |
| | Number of inverters | 1 | 1 | 1 | 1 |
| "EC motor EBM technology" | Plug fan | 1 | 1 | 2 | 2 |
| | EC motor | 1 | 1 | 2 | 2 |
| | Available power | | 1 kW | | |
| Pleated filters | | | G4 / M5 / F7 HEE / F9 HEE | | |
| Opacimetric filters (Short flexible pockets) | | | M6 / F7 | | |
| Opacimetric filters (Rigid pockets) | | | M6 / F7 / F8 / F9 | | |
| Hydraulic heating coil | | 1/2/3 rows | 1/2/4 rows | | 1/2/4 rows |
| Hydraulic cooling coil | | | 3/4/6 rows | | |
| Direct expansion cooling oil | | | 3/6 rows | | |
| **Heating/Cooling symetric power** | | 15 kW | 24 kW | | 33 kW |
| Adiacent plate heat exchanger | | Yes | Yes | | No |

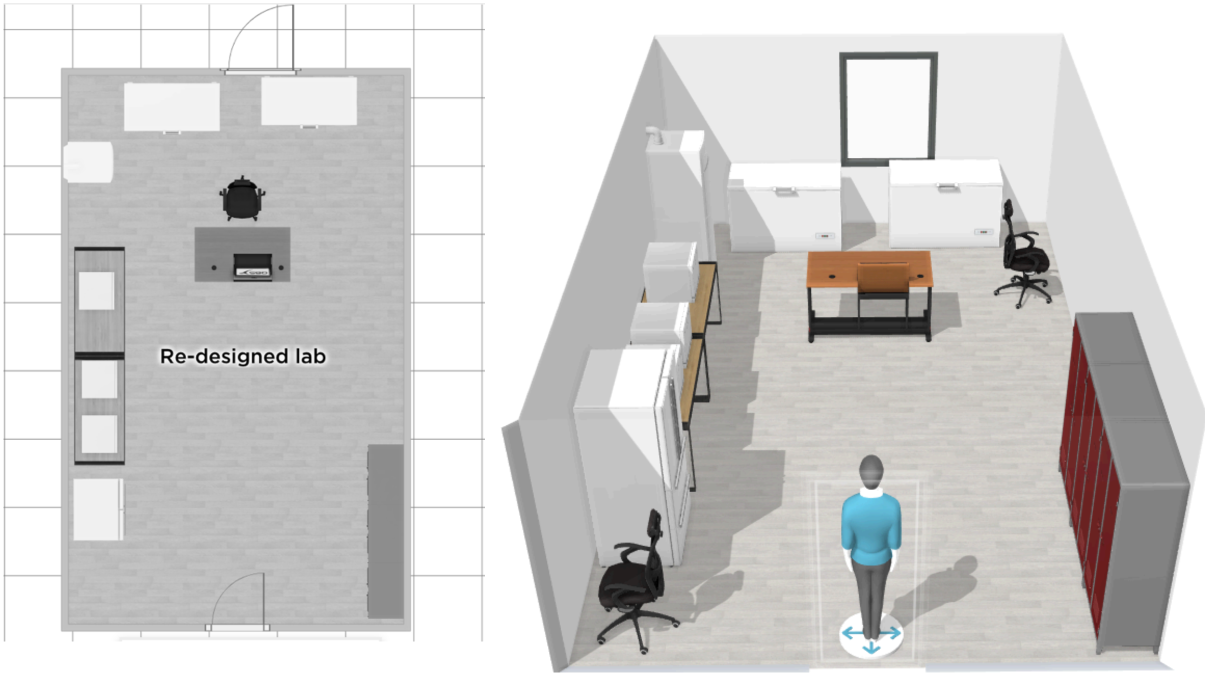



Fig. 23 - Layout re-design [Own elaboration]

A redesigned layout as proposed, would save 50% of space (48 $m^2$) which would result in an approximate saving of 20.000€ (calculated based on the price per square meter paid in Enschede)

### SOLUTION PRODUCTIVE IMPACT

In this section we will analyze the conclusions obtained regarding the productive impacts that Lean techniques have on the additive manufacturing production system.

It can be concluded that the Lean analysis and implementation should be carried out based on:

- Reduction or elimination of activities that do not add value. Increase in the reliability of the equipment.
- Order and cleaning.
- Standardization.

It is necessary that UTwente begins to make use of the indicators in Tab. 5, and above all, in the OEE indicator, to make an assessment over time of the improvements obtained by using the techniques and approach proposed in this thesis.

- Concluding, by means of Lean techniques, an excesive resource dependance reduction would be achieved in terms of change, which, as previously studied, represents 20% of the total production times in the printing process, achieving a significant increase in productivity, already stopped the stops for corrective maintenance.
- Optimization of space usage, saving 20.000€ of direct costs and yearly costs linked to various services as energy consumption or cleaning.
- By making an estimate, the materials must be reduced by 5% and it is estimated that 30% of the material can be reduced by reprocessing, color checks and wasted ink. Therefore, there is a 15% reduction in raw material.
- Decrease of 12.5% in energy, due to the decrease in preparation and change times.
- Reduction of Lead Time only applying Lean techniques to the printing process. A continuity and an expansion to the processes of the company is the basis to continue improving.
- Greater flexibility.

# 2. FINANCIAL AND SUSTAINABILITY ANALYSIS

The environmental awareness that exists today extends to all areas, including the one related to the realization of engineering projects makes this work also support this environmental commitment.

Manufacturing companies are one of the main causes of pollution, and therefore, must respect the environment and legality.

With reference to these terms, the dimension of sustainability of this work occurs in several axes. On the one hand, the improvement of the processes makes them more efficient and this implies a reduction of waste such as inks and paper or energy. On the other hand, the most efficient processes improve productivity and help the company's economic sustainability.

With all this, in this work we try to reduce the damage caused to the environment as much as possible and respect for the environment is guaranteed.

The total investment for the implementation of Lean techniques implies a total of € 4484 in the first month (accounting for Poka Yoke devices), € 1739 in the second and third months (training and TPM), and the costs derived from TPM since then.

On the other hand, the current costs / benefits of the works valued by the company are the following:

- 40% materials
- Labor 12%
- Operating costs (electricity, electricity ...) 20%
- Administrative costs 5%
- Service costs 6%
- Other 2%
- Benefit 15%

- In total the material is reduced by 15%, therefore, the economic weight of 40% is reduced to 34%.
- Energy saving of 12.5%. Therefore, operating costs are reduced from 20% to 17.5%.

- The total benefits of work increase from 15% to 23.5%, by reduction of raw materials and energy.

- The increase in benefit in the works can translate into an increase in the monetary benefit for work or also a reduction in the price that increases the competitiveness in the market, which is the objective of this work.

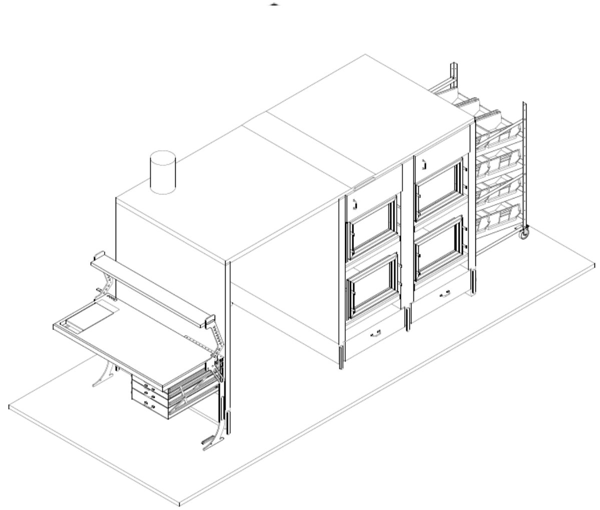
- One of the main advantages of the Lean is that productivity accelerates by 35% in the printing process approximately, which is the bottleneck. This supposes greater flexibility.

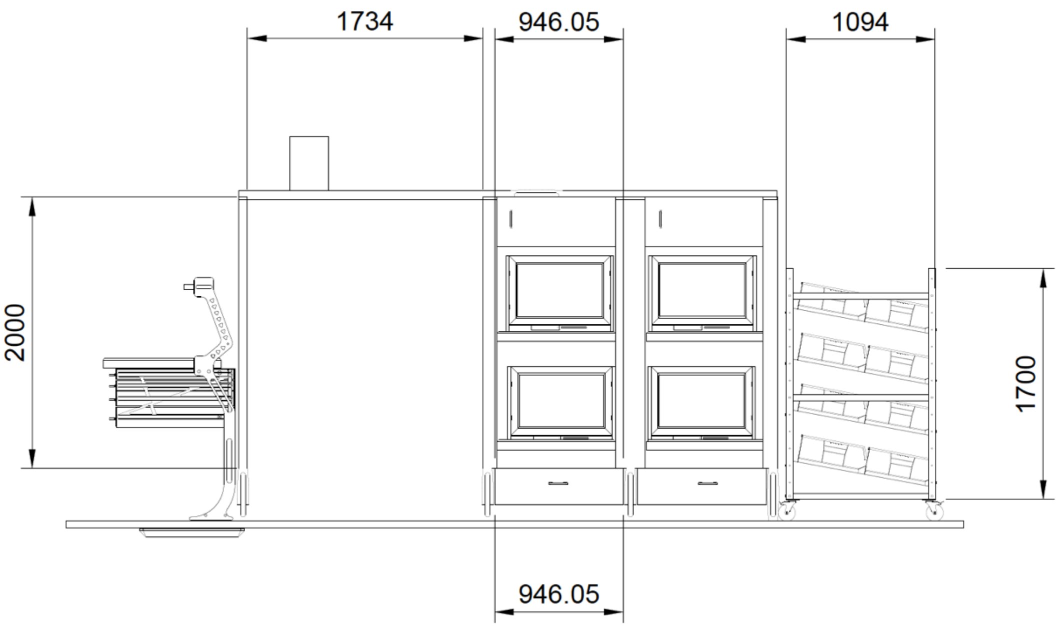
Taking into account that this SME currently has gross sales benefits of € 10,500 per month, increasing its gross profit based on the aforementioned for reductions in raw materials derived from Lean techniques and speeding up production in printing by around 35% by reducing non-productive times.

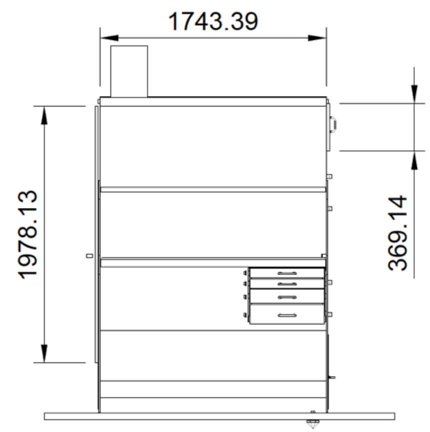
# IMPLEMENTATION COSTS

| | Ammount | Unit | Price p/u | Total |
|---|---|---|---|---|
| **PROJECT DEVELOPMENT** | | | | |
| Hours - Process Engineer | 150 | hours | 50,00 € | 7.500,00 € |
| Hours - Lean consultant | 120 | hours | 60,00 € | 7.200,00 € |
| **INSTALLATIONS AND ASSEMBLIES** | | | | |
| **Technical Workforce** | | | | |
| Hours - Technical Worforce (Assemblers) | 10 | hours | 25,50 € | 255,00 € |
| Hours - Technical Worforce (Installators) | 70 | hours | 25,50 € | 1.785,00 € |
| Hours - Non-qualified personnel | 5 | hours | 14,30 € | 71,50 € |
| **TRAINING** | | | | |
| **Personnel training costs** | | | | |
| Qualified | 60 | hours | 17,90 € | 1.074,00 € |
| Non-qualified | 60 | hours | 14,30 € | 858,00 € |
| **MATERIALS** | | | | |
| **Workstation materials** | | | | |
| 80x40 Container | 7 | units | 19,50 € | 136,50 € |
| LED lamp | 4 | units | 31,90 € | 127,60 € |
| Footrest | 2 | units | 29,50 € | 59,00 € |
| Magnetic holder | 10 | units | 3,00 € | 30,00 € |
| Information stickers | 20 | units | 0,10 € | 2,00 € |
| Thermal insulation material | 12 | m2 | 10,00 € | 120,00 € |
| Standardized cupboards | 4 | units | 40,00 € | 160,00 € |
| Glass doors | 4 | units | 750,00 € | 3.000,00 € |
| AHU (Air Handling Unit) | 1 | units | 2.324,00 € | 2.324,00 € |
| 316 Stainless steel (Hot rolled) - Pre-manufactured | 150 | kg | 65,00 € | 9.750,00 € |
| **Material storage** | | | | |
| Caliber for filament diameter (Material Extrusion processes) | 1 | units | 16,80 € | 16,80 € |
| PVC Filament holder (Material Extrusion processes) | 5 | units | 6,50 € | 32,50 € |
| Industrial vacuum cleaner (Powder Based processes) | 1 | units | 197,99 € | 197,99 € |
| Magnetic holder | 10 | units | 3,00 € | 30,00 € |
| Information stickers | 20 | units | 0,10 € | 2,00 € |
| **3D Printing process** | | | | |
| Software - Direct communication platform between laboratory and client | 1 | development | 700,00 € | 700,00 € |
| Printer bumps registration sheet | 50 | units | 0,15 € | 7,50 € |
| Evaluation form (sent to the client) | 1 | online units | 0,00 € | 0,00 € |
| Delivering branded packages | 100 | units | | 0,00 € |
| "Problems found during printing" sheet with part id. | 100 | units | 0,10 € | 10,00 € |
| Room smart thermostat | 1 | units | 249,00 € | 249,00 € |
| **Lean material** | | | | |
| Kanban shelf | 1 | units | 550,00 € | 550,00 € |
| **TOTAL BUDGET** | | | | **36.248,39 /** |

# 3. BLUEPRINTS.






FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISED

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | JUAN GARCÍA | | 03/18 |
| CHKD | | | |
| MFG | | | |
| Q.A | | | |

MATERIAL:

WEIGHT:

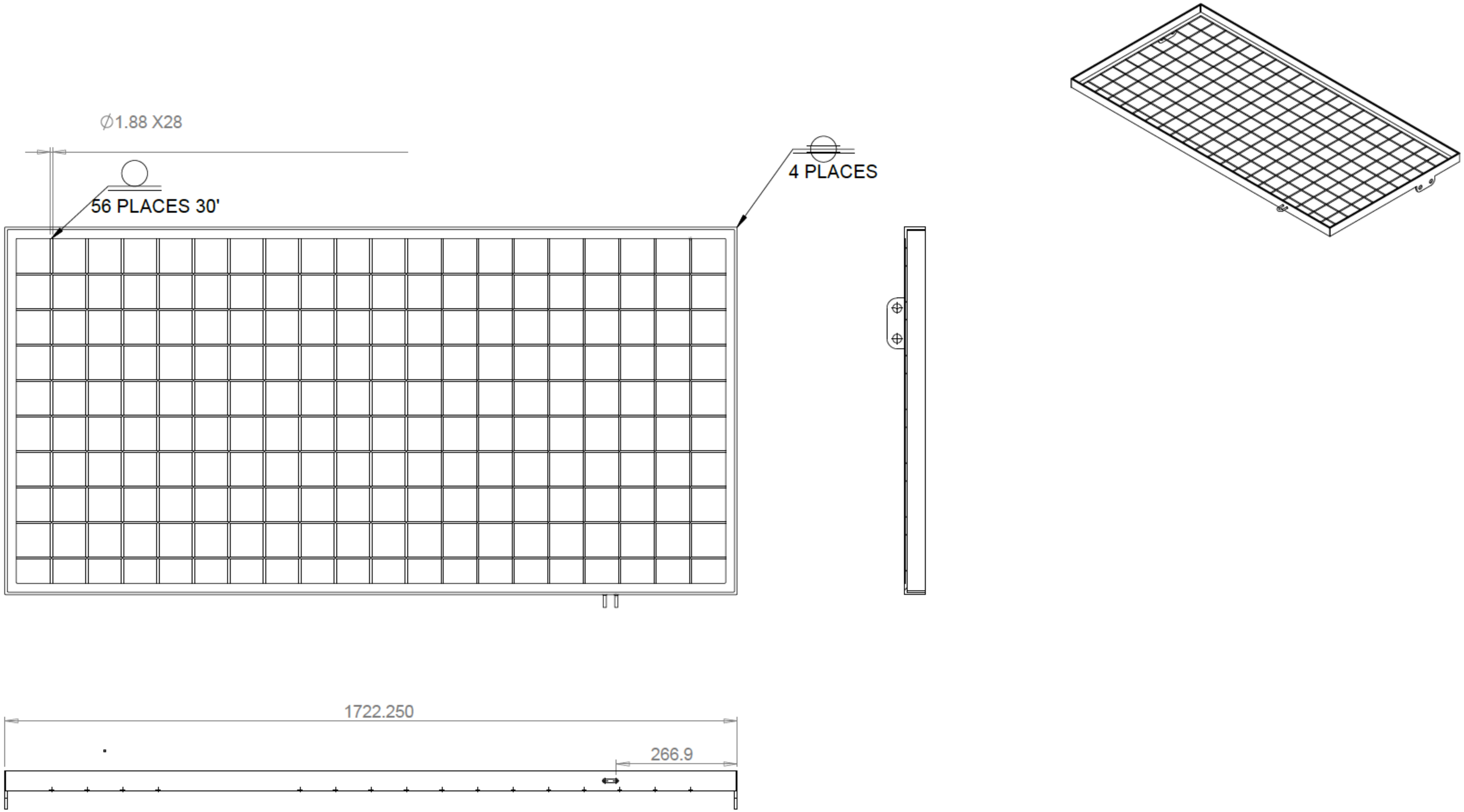
TITLE:

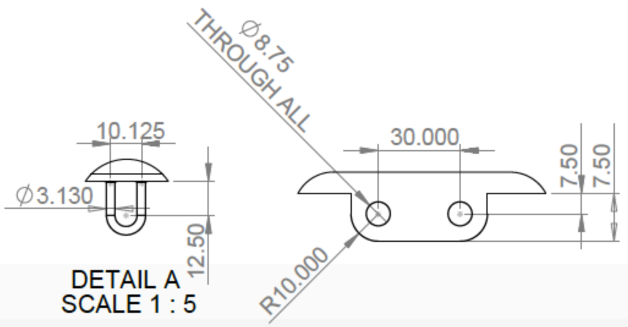
WORKING STATION

DWG NO.

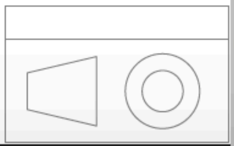
A3

SCALE:1:1




DETAIL A
SCALE 1 : 5



| | | | | |
|---|---|---|---|---|
| FINISH: | | DEBUR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISED |
| | NAME | SIGNATURE | DATE | |
| DRAWN | JUAN GARCÍA | | 03/18 | |
| CHKD | | | | |
| MFG | | | | |
| Q.A | | | | |

MATERIAL:

WEIGHT:

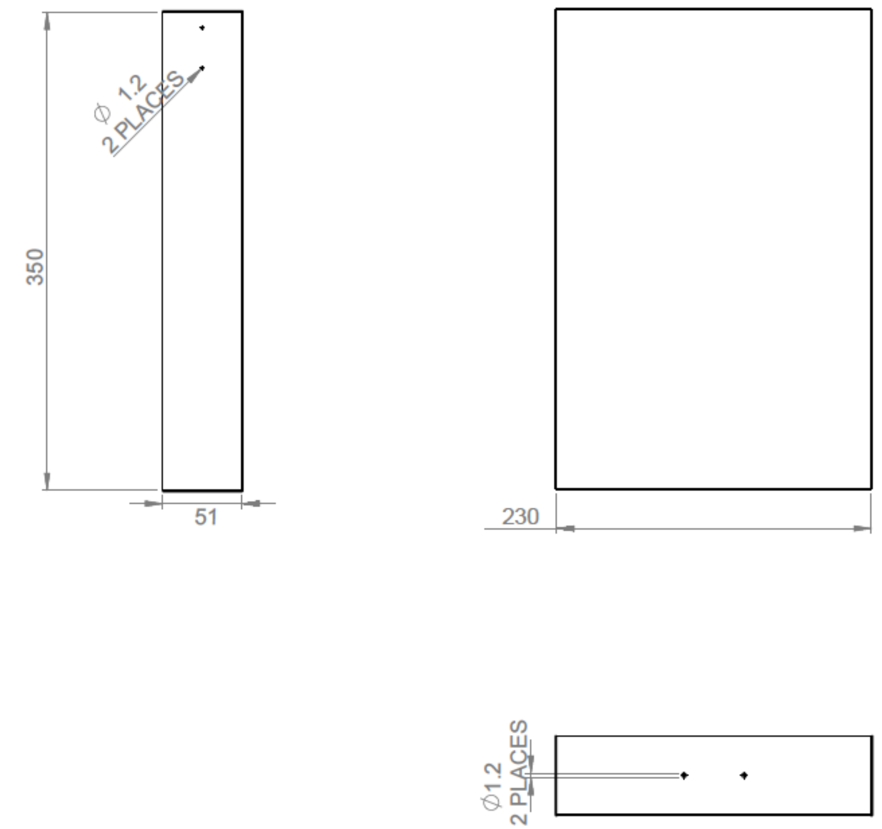
TITLE:

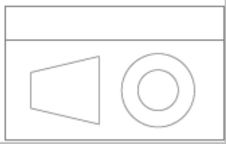
SLS COMPARTMENT - BACK NET

DWG NO.

A3

SCALE:1:1



FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISED

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | JUAN GARCÍA | | 03/18 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

TITLE:

STATION WALLS

MATERIAL:

STAINLESS (304)

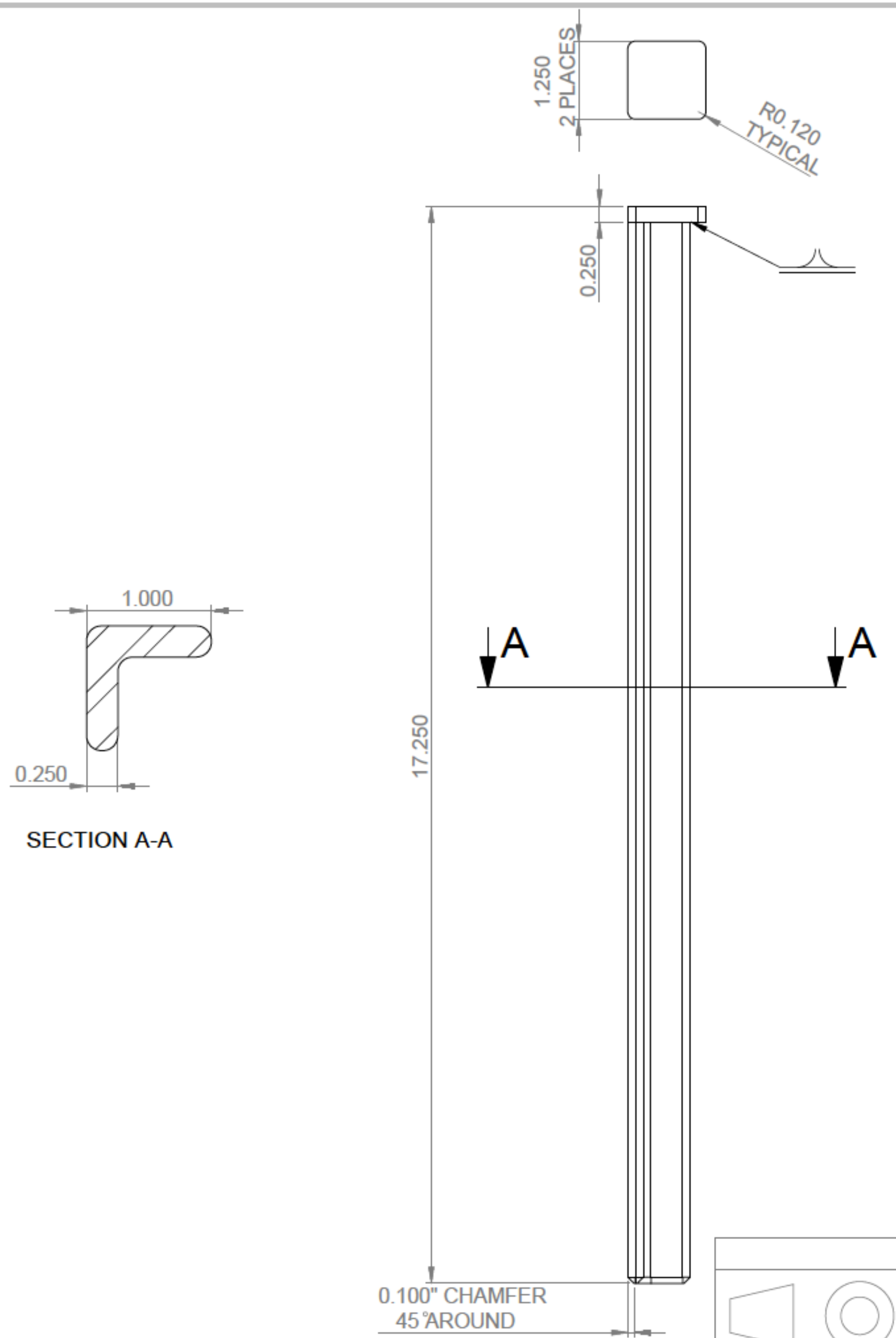
DWG NO.

A3

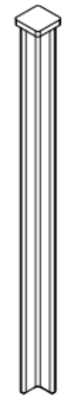
WEIGHT:

SCALE:1:1

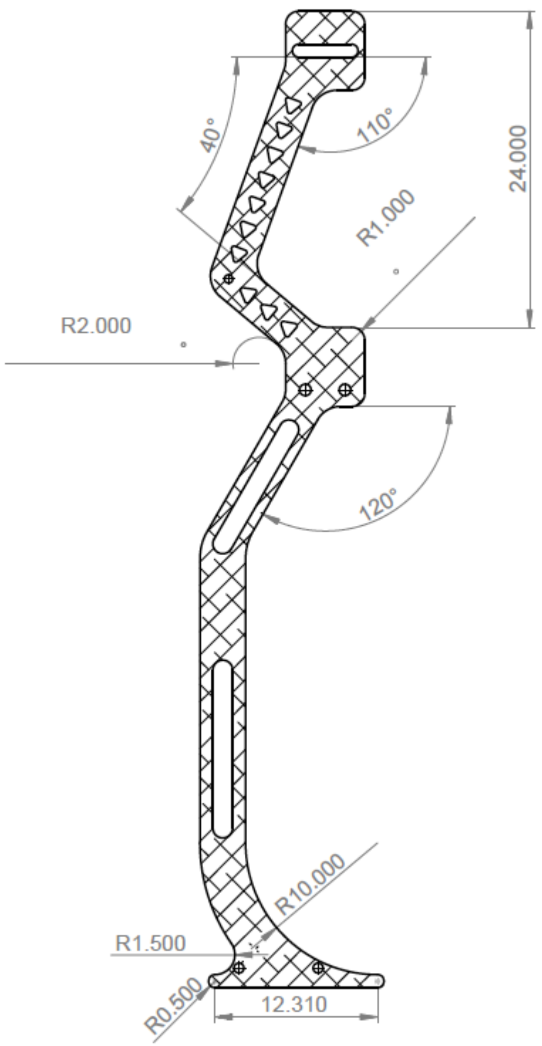
SHEET 6 OF 14



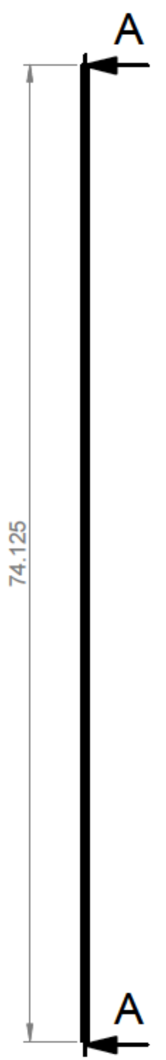

SECTION A-A

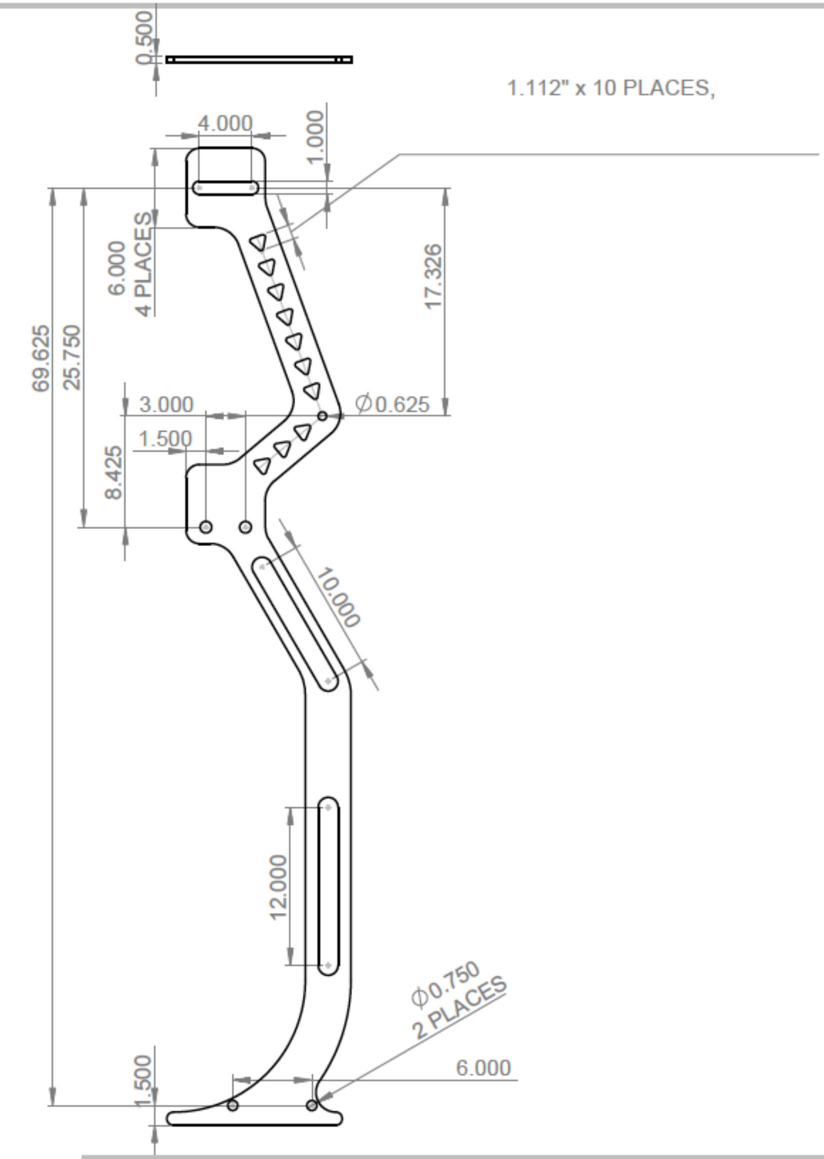


| | | | | | |
|---|---|---|---|---|---|
| FINISH: | | DEBUR AND BREAK SHARP EDGES | | REVISED | |
| | NAME | SIGNATURE | DATE | TITLE: | |
| DRAWN | JUAN GARCIA | | 03/18 | HANGER STRUCTURE | |
| CHK'D | | | | | |
| APPV'D | | | | | |
| MFG | | | | | |
| Q.A | | | MATERIAL: STAINLESS | DWG NO. | A3 |
| | | | WEIGHT: | SCALE:1:1 | SHEET 2 |




SECTION A-A
SCALE 1 : 10




FINISH: ANODIZED

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | JUAN GARCIA | | 29/03/18 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

MATERIAL: 7075-T5

WEIGHT:

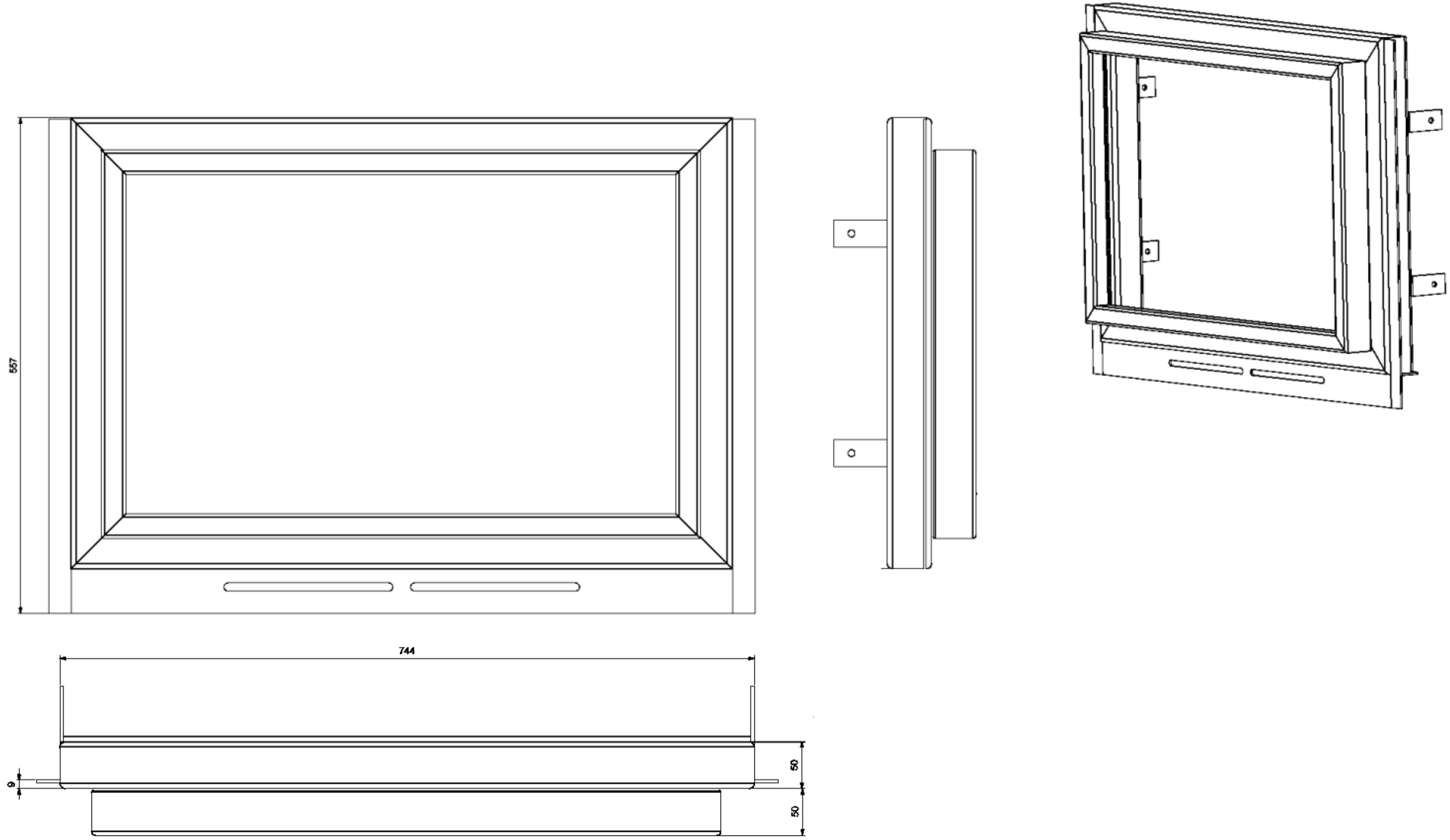
TITLE: SHELF SUPPORT

DWG NO.

A3

SCALE:1:1

SHEET 3




FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISED

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | JUAN GARCÍA | | 03/18 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

MATERIAL: GLASS AND SS

WEIGHT:

TITLE: GLASS DOOR

DWG NO.

A3

SCALE:1:1

SHEET 6 OF 14

# 4. CONCLUSIONS. FUTURE WORK.

- The bottleneck of the company remains unclear, and therefore, the focus of improvement to increase the productivity of the company is divergent.
- Problems with defective parts can be solved through the application of Lean Manufacturing techniques.
- The main problems detected in the processes are human and environmental and very high changes, which are accentuated by constant breakdowns, reprocesses and incidents, which are repairable through this new approach.
- To improve production, neither cutting-edge technology nor very high investment is required, but with simple and well-implemented ideas, great results can be achieved.
- A change in the culture is vital to obtain lasting and not momentary results, avoiding to fall back into the mistake.
- Good results will only be achieved by a real commitment of all the people that make up the company, from the management to the operators.
- To be able to function as a sustainable company it is essential to apply all the techniques as a whole and not in isolation.
- A frequent monitoring mechanism is necessary to provide evidence of possible improvements.

# 5. REFERENCES

[BAUM12] Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond, E., & Hague, R. (2012). Combined build-time, energy consumption and cost estimation for direct metal laser sintering. In *From Proceedings of Twenty Third Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference* (Vol. 13).

[GANS04] de Gans, B. J., Duineveld, P. C., & Schubert, U. S. (2004). Inkjet printing of polymers: state of the art and future developments. *Advanced materials*, *16*(3), 203-213.

# 6. APPENDIX SECTION

## 6.1 APPENDIX I: VOICE OF THE CUSTOMER SURVEY

### UTwente Additive Manufacturing Laboratory

**Customer Satisfaction Survey**

Thank you for ordering  from us. Please take a moment to tell us about your experience and how well our additive manufacturing service has been meeting your expectations.

1. What products and services have you purchased from us?

   ☐ Rapid prototyping

   ☐ Rapid manufacturing

2. Overall, how satisfied are you with your experience?

   ☐ Very satisfied

   ☐ Satisfied

   ☐ Neutral

   ☐ Dissatisfied

   ☐ Very Dissatisfied

3. Would you share your main needs when asking for an AM service?
   ______________________________________________________________________
   ______________________________________________________________________
   ______________________________________________________________________
   _______________________________________

4. Please rate the following characteristics you value the most:

| | **Excellent** | **Satisfied** | **Neutral** | **Dissatisfied** | **Very dissatisfied** |
|---|---|---|---|---|---|
| **Functionality** | | | | | |
| **Tolerances** | | | | | |
| **Reasonable delivery** | | | | | |
| **Professionalism** | | | | | |
| **Ability to meet needs** | | | | | |

5. Will you likely use our services again? (optional)

   ☐ Yes

   ☐ No

   ☐ Not sure

   If not, why not?

   ____________________________________________________________________________
   ____________________________________________________________________________
   _________

6. Would you recommend us to a colleague or friend?

   ☐ Yes

   ☐ No

   ☐ Not sure

7. Do you have any additional feedback or any other suggestions for improving our services?

## 6.2 APPENDIX II: FORMIGA P110 TECHNICAL DATA

P-Solutions


Plastic laser sintering system **FORMIGA P 110**
for the direct manufacture of series,
spare parts and functional prototypes

## Technical Data

| | |
|---|---|
| Effective building volume | 200 mm x 250 mm x 330 mm |
| | (7.9 x 9.8 x 13 in, excl. pyrometer measurement spot) |
| Building speed (depending on material) | up to 20 mm height/h (0.79 in/h) |
| Layer thickness (depending on material) | 0.06 mm (0.0024 in), 0.1 mm (0.0039 in), 0.12 mm (0.0047 in) |
| Support structure | not required |
| Laser type | $CO_2$, 30 W |
| Precision optics | F-theta lens |
| Scan speed during building | up to 5 m/sec (16.4 ft/se.) |
| Power supply | 16 A |
| Power consumption | 2 kW |
| Nitrogen generator incl. external nitrogen connection | integrated |
| Compressed air supply | min. 6,000 hPA (87 psi); 10 m3/h (13.08 $m^3$) |

### Dimensions (B x T x H)

| | |
|---|---|
| Machine with powder containers and touch screen | 1,320 mm x 1,067 mm x 2,204 mm (51.97 x 42.01 x 86.77 in) |
| Weight | approx. 600 kg (1,323 lb.) |
| Unpacking and sieving station (optional) | 1,200 mm x 700 mm x 1,500 mm (47.24 x 27.56 x 59.06 in) |
| Powder mixing station (optional) | 700 mm x 500 mm x 1,000 mm (27.56 x 19.69 x 39.37 in) |

### Data preparation

| | |
|---|---|
| Software | EOS RP Tools (optional); Desktop PSW |
| Data interface to CAD system | STL (optional: converter to all common formats) |
| Network | Ethernet |

# Technical specifications

## Ultimaker 3

RPLab

| | |
|---|---|
| *Process* | Fused deposition modeling (FDM) |
| *Printer head* | Dual extrusion |
| *Effective building volume* | Left nozzel; 215 x 215 x 200 mm<br>Right nozzel; 215 x 215 x 200 mm<br>Dual nozzel: 197 x 215 x 200 mm |
| *Building speed (depending on material)* | 0.40 nozzle; up to 16 $mm^3/s$ |
| *Layer thickness (depending on material)* | 20 - 200 micron |
| *XYZ accuracy* | 12.5 / 12.5 / 2.5 micron |
| *Support structure* | ABS, PLA, PVA (solvible) |
| *Nozzel diameter* | Left nozzel; 400 micron<br>Right nozzel; 400 micron |
| *Nozzel temperature* | 180 - 280 $^0$C |
| *Filement diameter* | 2.85 mm |
| *Build plate* | Heated glass build plate |
| *Build plate temperature* | 20 - 100 $^0$C |
| *Power supply* | 100-240V, 4A 50-60Hz |
| *Power consumption* | 0.22Kw |
| *Material* | ABS, PLA, PA, CPE, PVA (solvible) |

# Technical specifications

# Form 2

RPLab

| | |
|---|---|
| Process | Stereolithography (SLA) |
| Effective building volume | 145 × 145 × 175 mm |
| Layer thickness (depending on material) | 25 - 100 microns |
| Laser type | Violet laser 405nm, 250mW |
| Laser spot size (FWHM) | 140 microns |
| Operating temperature | Auto-heats to 35 °C |
| Peel Mechanism | Sliding Peel Process with wiper |
| Resin fill system | Automated |
| Power supply | 100-240V, 1.5A 50/60 Hz |
| Power consumption | 0.65kW |
| Material | Resin material (see material specs) |
| Support structure | Required, auto-generated, easily removable |

Alberto Aguilera 25
7522 DB Madrid (España)
Tel +34 91 779 4300
**www.comillas.edu**