The design and production by additive manufacturing: case of face shields

O projeto e a produção por manufatura aditiva: caso dos protetores faciais.

DOI:10.34117/bjdv8n4-163

Recebimento dos originais: 21/02/2022
Aceitação para publicação: 31/03/2022

Andréa Cristina dos Santos
Doutorado
Instituição: Departamento de Engenharia de Produção, Universidade de Brasília
Endereço: UnB - Brasília, DF, CEP: 70910-900
E-mail andreasantos@unb.br

Alexandre Crepory Abbot de Oliveira
Doutorando
Programa de Pós-Graduação em Engenharia Elétrica
Instituição: Universidade de Brasília
Endereço: UnB - Brasília, DF, CEP: 70910-900
E-mail: alex.crepory@gmail.com

Tiago Camargo Alves
Mestre
Programa de Pós-Graduação em Sistemas Mecatrônicos
Instituição: Universidade de Brasília.
Endereço: UnB - Brasília, DF, CEP: 70910-900
E-mail: tiago.camargoalves@gmail.com

Joao Vitor Quintiliano Silveiro Borges
Mestrando
Laboratório Aberto de Brasília, ULEG, Faculdade de Tecnologia, UnB, Campus Darcy Ribeiro, Brasília – DF
Instituição: Universidade de Brasília
Endereço: UnB - Brasília, DF, CEP: 70910-900
E-mail j.quintiliano@gmail.com

Leandro Bruno Alves Caio
Doutorando
Programa de Pós-Graduação em Sistemas Mecatrônicos, Universidade de Brasília
Instituição: Universidade de Brasília
Endereço: UnB - Brasília, DF, CEP: 70910-900
E-mail engleandrocaio@gmail.com

ABSTRACT
Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) quickly reached a global pandemic status in 2020 creating a huge demand for personal protective and medical equipment. Additive manufacturing, in this context, became a solution to

alleviate the demands of the healthcare sector. This article presents how lean manufacturing approaches and Design for Additive Manufacturing (DfAM) helped to implement an additive manufacturing line for face shields production. The methodological approach was action research, in which undergraduate and graduate students, professionals, and researchers joined forces to produce and deliver 27,000 face shields. The article contributes towards the implementation of additive manufacturing for small batches production of product final parts and offers content for future discussions regarding production digitization.

Keywords: additive manufacturing, design for additive manufacture (dfam), lean manufacturing, product design.

RESUMO
O Coronavírus 2 (SRA-CoV-2) da Síndrome Respiratória Aguda Severa atingiu rapidamente um estatuto pandémico global em 2020, criando uma enorme procura de equipamento médico e de protecção pessoal. A fabrica de aditivos, neste contexto, tornou-se uma solução para aliviar as exigências do sector da saúde. Este artigo apresenta a forma como as abordagens de fabrico enxuto e o Design for Additive Manufacturing (DfAM) ajudaram a implementar uma linha de fabrico de aditivos para a produção de escudos faciais. A abordagem metodológica foi a investigação de acção, na qual estudantes de graduação e pós-graduação, profissionais e investigadores uniram forças para produzir e fornecer 27.000 escudos faciais. O artigo contribui para a implementação do fabrico de aditivos para a produção de pequenos lotes de peças finais de produtos e oferece conteúdos para futuras discussões relativas à digitalização da produção.

Palavras-chave: fabrica de aditivos, design para fabrica de aditivos (dfam), lean manufacturing, design de produto.

1 INTRODUCTION

Additive manufacturing (AM) can be understood as a new type of industry that uses computer-controlled machines to directly transform digital designs into physical products. This includes technologies that use material deposition methods to develop two-dimensional or three-dimensional structures. (VOLPATO, 2017).

Over the past 30 years, the use of AM technologies has transformed. It started with applications for the production of prototypes and, today, the technology is becoming an option for the production of final parts (THOMPSON et al., 2016; SILVA et al, 2020). Studies carried out by Beltrami and Orzes (2021) points to the potential for new businesses for small and medium-sized companies from the use of AM.

However, the lack of knowledge about the capabilities and limitations of additive manufacturing processes is pointed out by Li et al. (2019) and Pradel et al. (2018) as a barrier to adopting additive manufacturing to produce final parts. The implementation should not be done considering recommendations for solutions and knowledge based on traditional manufacturing to design and produce parts (GARCIA-DOMINGUEZ; CLAVER; VICTHOR, 2020) or even through trial and error (TAREQ ET AL., 2021), presenting the need for knowledge about Design for Additive Manufacturing (DfAM).

The purpose of this paper is to present how Design for Additive Manufacturing (DfAM) and Lean Manufacturing (LM) contributed to the implementation of the face shield production line through additive manufacturing.

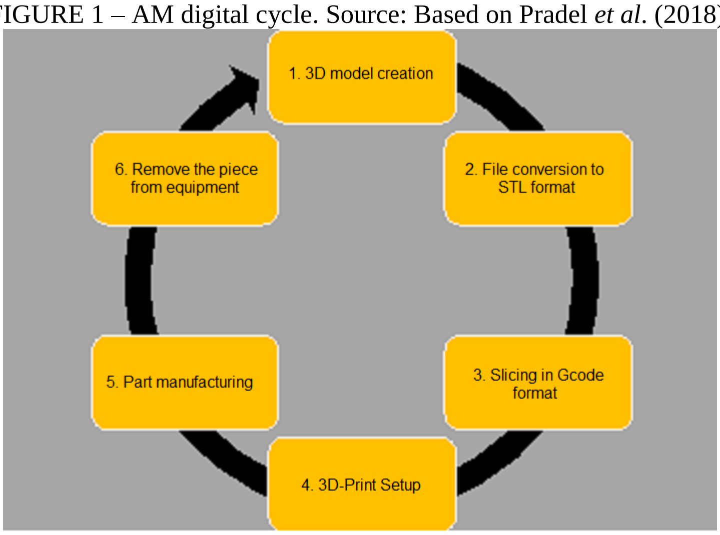
2 LITERATURE REVIEW

2.1 DESIGN FOR ADDITIVE MANUFACTURING (DfAM)

Additive Manufacturing advances are bringing new design possibilities and breaking production paradigms. While a lot of work is needed to bring DfAM to maturity, large and small companies continue to explore the adoption of AM for final parts. The DfAM is still in development (THOMPSON et al., 2016). Its scope of action has been broader when compared to traditional Design for Manufacturing Assembly (DfMA) approaches.

Figure 1 presents the AM digital cycle, which usually brings traces of iterations, starting with the modeling of a 3D model, with a traditional approach in Computer-Aided Design (CAD), converted into Standard Triangle Language (STL) file format to be separated in layers by a digital slicing process and translated in machine control language, denominated G-code. After the machine is set up, the part is manufactured and post-processed to its finished form. The slicing process is performed considering the manufacturing parameters and machinery.

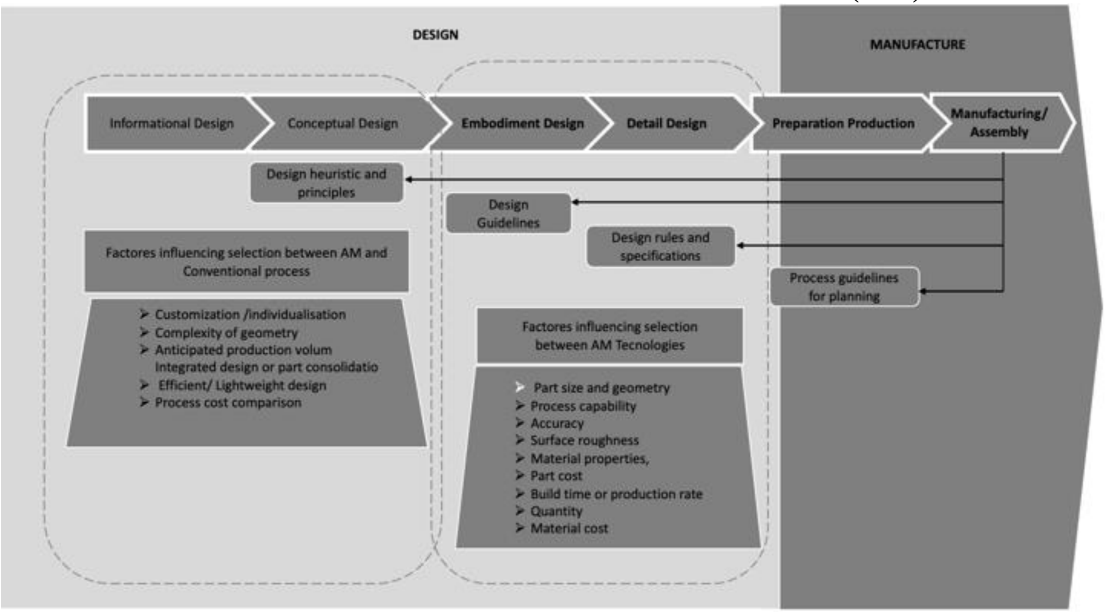
FIGURE 1 – AM digital cycle. Source: Based on Pradel *et al*. (2018).



Different approaches have been proposed to organize DfAM beyond the "digital cycle". There is a different approach of literature review liter about DfAM, such as the works by Pradel et al. (2018), Ponche et al. (2012), Boyard et al. (2014), Yang et al. (2015), Kumke et al. (2016), and Rosso et al. (2021). These approaches to DfAM consider the entire Product Development Process (PDP), adapting phases and deliverables for the development process based on the characteristics of additive manufacturing. Figure 2 presents a model proposed by Pradel et al. (2018).

Different factors need to be considered in the product development process (PDP) to optimize products for production through additive manufacturing. There are gaps in the literature review about how are produced small batches of products or pieces by additive manufacturing.

FIGURE 2 – DfAM framework. Source: Based Pradel *et al*. (2018).



2.2 ADDITIVE MANUFACTURING OPPORTUNITY FOR LEAN MANUFACTURING

According to Womack and Jones (2005), the main proposal of the lean philosophy is to continuously optimize the delivery of value to the customer. AM has potential to be optimized by Lean Manufacturing (LM). Biazzo, Panizzolo and Gore. (2017) relate the importance of the value principle for AM, especially in prototyping for clients in the context of PDP (Product Development Process). Ghobadian *et al*. (2018) state that LM integrated with AM can legitimize the elimination of waste by reducing time to market; reduced setup times; reduction of processing steps; reduced energy requirements; improvement in the quality of parts; reduction in the need for rework, improvement in the finishing of parts; possibility of manufacturing complex parts. In addition to enabling the reduction of total production costs and shortening the supply chain. The Table 1 presents opportunities to enhance AM with LM principles.

Table 1 – Opportunities for the employment of Additive Manufacturing for Lean Manufacturing. Source: Authors

Lean approach	AM Employment Opportunities	References
Business	Custom production in a distributed environment Mass customization of products.	Khajari *et al.* (2014) Gao et al. (2015)
Product Design	Complex geometries changes and updates can be performed more easily. Optimization of the weight of parts based on the freedom to manufacture geometries. Provides the manufacture of channels and internal structures that increase component functionality and performance. Surface finishes and textures and custom porosities.	Thompson *et al.* (2016) Asadollahi-Yazdi *et al.* (2017) Rosso *et al.* (2021) Gibson *et al.* (2014). Ponche *et al.* (2012) Diegel *et al.* (2019)
Manufacturing	Reduction of the time to market. Reduction of Setup times. Reduction of processing steps. Reduction of energy requirements. Reduction in the need for rework and finishing of components.	Oettmeier, Hofmann (2016) Ghobadian *et al.* (2018) Gibson *et al.* (2014).
Supply Chain	Reduce shipping costs and reduce delivery times. Produce parts on-demand and thus reduce the need to maintain a safety inventory. Shortening of supply chain links.	Liu *et al.* (2014) Ghadge *et al.* (2018) Ghobadian *et al.* (2018)

Lean is based on the concept that any activity/action that fails to create value for customers is waste and must be reduced (BIAZZO, PANIZZOLO, GORE, 2017). Therefore, for a system to be lean, it must address the reduction of variability in the relationships for the unit of analysis.

Pabliosa *et al* (2021) seeking to integrate Industry 4.0 concepts with LM present the main methods, techniques, and tools for the operation (Kanban, Value Stream Mapping, Poka Yoke, Kaisen, Pull Production, Andon, SMED, standardization, TQM, Takt Time, Heijunka, 5S, Jidoka and TPM).

3 METHODOLOGY

The research question that conducted this work was how to maintain a small production line for final products produced by additive manufacturing. The origin of this research was the production of face shield using AM to fight the COVID-19 pandemic. So, this research sought to contribute to the implementation of AM for the production of final parts.

The methodological approach was action research, in which undergraduate and postgraduate students, professionals, and researchers joined forces to produce and deliver 27,000 face shields in Brazil's Federal District. The rationale for selecting the method was due to interference in the middle of the study, with interactions between researchers and those involved being conducted in real-time.

The steps for the development of action research were researched planning, data collection, data analysis, action planning, implementation, evaluation of results, and reporting.

In 2017, the Open Laboratory of Brasília – LAB was opened at the University of Brasília (UnB), Technology Faculty. In which Fused Deposition Modeling (FDM) printers were acquired, with an approach centered on the production of prototypes. In 2020, due to the Pandemic installed by COVID-19, temporary production was requested on an emergency basis to produce face shields.

The production of face shields by AM to fight the COVID-19 pandemic was carried out on an emergency and temporary basis, occupying the entire building of the Undergraduate Teaching Unit of the Faculty of Technology at UnB, which is the seat of the Open Laboratory of Brasília. The production was made possible because the entire building was closed to other academic activities, which allowed the use of as many areas as necessary and to create safety protocols.

The planning stage was based on Oppenheim (2004), mainly due to the team size and the characteristics of the project. A project leader, a project room, the analytical structure with the deliverables, the workflow, the availability and visualization of the data, and the results generated were defined. The initial team consisted of four postgraduate students and 30 undergraduate students. Four members dominated AM processes, with knowledge acquired through training and experience at the laboratory. Ten members were trained during the project, gathering the team without any experience with additive manufacturing processes.

During the planning, an exploration of the specialized literature was carried out, used to support decisions throughout the action research. Part of this activity is presented in the previous section.

The techniques used to conduct the action research phases involved: direct observations, analysis of existing records, training, planning meetings, activity execution, results in analysis, and reporting.

4 THE DESIGN AND PRODUCTION OF FACE SHIELD

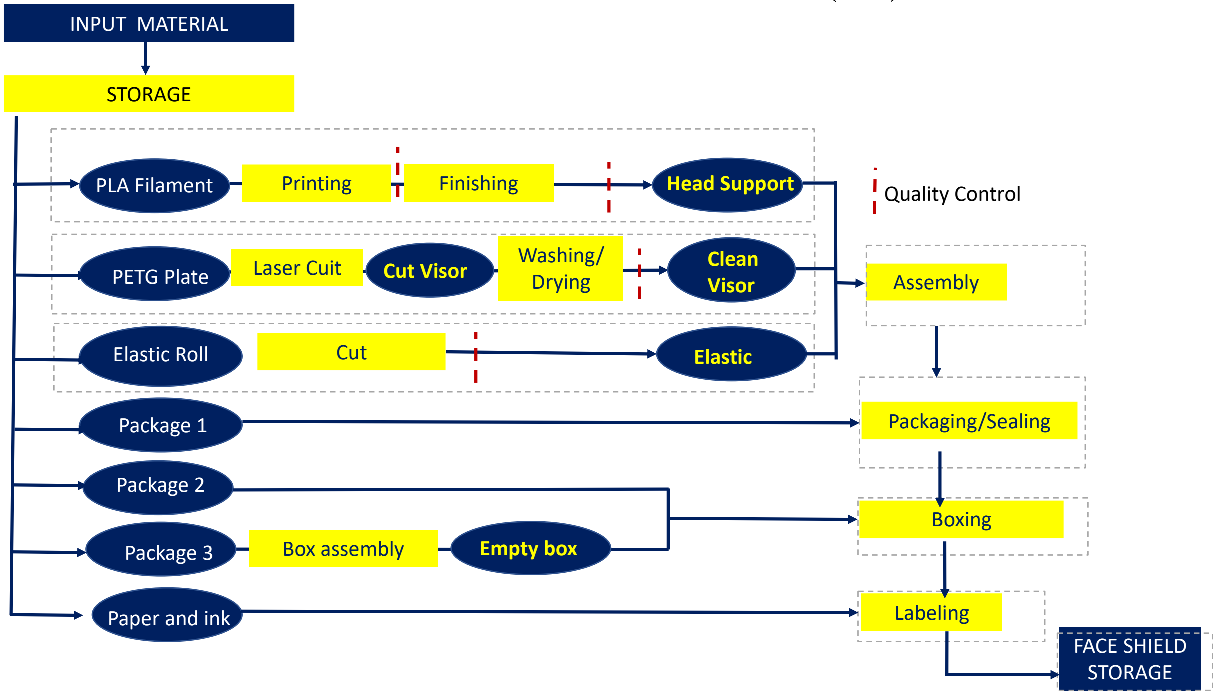
At the Design's inception, the legal requirements were explored, the device for the health sector is regulated by the Brazilian National Health Surveillance Agency (ANVISA). In the extreme situation of pandemic control, ANVISA authorities published the standard RDC n.356 on 03/23/2020, making necessities and regulations more flexible for healthy products manufacturing. Even with the changes, there were references to other standards to produce health workforces that were not made more flexible. These standards guided the project in terms general of the production flows, inspection, and quality control points. To control the product line, the team members create a manual for product quality control and guides for best practices for manufacturing.

Based on legal requirements, in a survey with the health professionals' needs; and on the technologies available at the LAB (FDM printers). It decided to select an internationally validated product, which was developed by Prusa 3D company, headquartered in the Czech Republic (PRUSA 3D, 2020) because it was open source. The product developed by the company consisted of three parts, head support, a large visor that provides complete protection of entire face, and an elastic band to ensure proper fitting.

However, it was necessary to review the design completely. In the manufacturing stage, the best part quality and printing time results were obtained with a single part per machine, using the DfAM approach as a theoretical reference.

Figure 3 represents the flow of the product manufacturing process. This presents the material entries: PLA filament, PETG Plate, Elastic Roll, Surgical Paper (primary packaging), Plastic Bag (secondary Package 2), Cardboard Box (tertiary Package 3), and paper and ink for product labeling. The steps of manufacturing: 3D printing and scraping (post-processing) for the head support; Laser cutting, to obtain the transparent display final geometry, followed by washing and drying steps; and the elastic band cutting process. In the assembly stage, the parts were integrated and assembled, forming the face shield produced. Another major advantage for the model developed by Prusa 3D is presented at the assembly process where the entire assembly does not need any type of fastener.

FIGURE 3 – Process flowchart. Source: LAB Archive (2020)



The project started and was carried out for three months, using only seven FDM printers. At the beginning of the fourth month, new printers were acquired to expand the production; two rooms with 25 FDM printers each were implemented. Figure 4 illustrates both production floors.

The selection for machinery with FDM technology was due to its ease of maintenance since all maintenance and calibration were carried out by the students themselves.

FIGURE 4 – Printing Rooms 1 and 2 Source: LAB Archive (2020)

One of the process control indicators was the availability of machines. Figure 5 illustrates the monitoring of the printing process. Based on data for the period from September 2020 to January 2021, the machine availability indicator was 98.3%. From the data analysis, it was identified that the machine stoppages were mainly associated with human error.

FIGURE 5 – Monitoring the 3D printing process. Source: LAB Archive (2020)

A traceability system was developed, with data from the production process, presented in Annex A. Data modeling focused on the principles for real-time management, interoperability, virtualization, decentralization, agility, and service orientation.

In this project, due to the urgency and emergency, most of the product data and process controls were performed in a traditional way. The theoretical basis on the possibilities of data digitization was introduced in the discussions of meetings and training of the team. As a result, a set of needs and requirements for future projects was obtained.

Another indicator used during manufacturing was the demanding rhythm (Takt Time). To maintain stability in the process, it was necessary to implement other LM tools: standardized work (standard operating procedures) 5S, Jidoka, and Kanban. These tools were selected based on the production operating time and the need for training in a short period.

In addition to the operational patterns described above, visual patterns were created. In Figure 6, examples are presented with different types of anomalies in the output of the printing process.

FIGURE 6 – Anomalies in the printing process. Source: LAB Archive (2020)

Regarding the 5S, the spaces were organized to minimize any errors. Minimum tools and materials were used on-site, in addition to visual identification. The main theories of LM used for the project were Jidoka, Kanban, workforce stability, and materials stability.

To ensure the automation with a human touch proposed by **Jidoka** principles; employees were required to carry out a detailed analysis of the items' potential defects throughout the manufacturing process. At the beginning of operations, it was natural for the employee to identify a greater number of errors; the time of execution of the activity there was less effective in identifying the failures. To minimize exaggerated quality and effectiveness in identifying potential fault a double-check was carried out, the first referring to disapproved items and the second in releasing the item for the next process step.

Kanban was used in conjunction with the production pace. The project team had information on the production progress and kept up-to-date on daily production targets. Moreover, the stability of the production process is dependent on the workforce stability and materials stability:

Workforce stability requires that the employees have training. To know what to do, how to do it, and when to do it. The training involves how to develop the tasks, and develop a critical sense to improve them. An example, It's the assembly process of the face shield. Several configurations of the product assembly flow were tested. The objective was to optimize assembly times and the number of members involved. Figure 7 illustrates an optimized assembly setup.

FIGURE 7 – Configuration of the face shield assembly process step. Source: LAB Archive (2020)

Materials stability means obtaining materials in the necessary quantity and quality at the workstations, preventing from being interrupted due their lack or defect production. I was defined a person for moving the material in areas. This person is responsible for early turn each checking the available materials, supply of materials and, collecting information about losses generated at the workstation.

The development of new versions of the face shield was motivated to reduce costs associated with the manufacturing stage and improve the quality of the product delivered to users. From the data by employing the methodologies of value engineering, product usability, and mechanical resistance tests. New versions of the product were developed.

The new supports developed with less mass and greater face protection achieved a 25% cost reduction compared to the original version developed by PRUSA 3D. Figure 8 shows the different versions of the product.

During the entire project, there was a direct channel for feedback with users of the face shield, via the patient quality centers of the hospitals. This communication aimed to identify possible improvements to the product and manage production and demand for face shields.

FIGURE 8 – Face shield versions. Source: LAB Archive (2020)

During the project, there were problems in the supply of inputs. At first due to constant lockdowns, second due to the resumption of activity in the supply chains which prioritize longer-term customers.

Table 2 presents the synthesis of the results obtained by the use of DfAM and Lean Manufacturing in the production of the face shield.

Table 2 – Synthesis of the results obtained with the Lean approach and the opportunities of AM. Source: Authors

Lean approach	**Results/DfAM e ML**
Business	- Reduced insertion time of delivery of new versions of the product. - Ease of expansion of the production scale. - Implementation of a low-cost additive manufacturing line.
Product Design	- Easy surface finishing and customized porosity. - Reduction of design changes costs. - Reduced response time to improve functional and performance requirements. - Reduced volume and weight per item. - Reduced print time per unit. - Co-development: health professionals and DIVISA/DF. - Time of changes and updates in 1 day.
Manufacturing	- Reduction of costs per unit produced. (R$130.00 to R$9.50 per unit). - Quick setup: 5 minutes. - Machine availability: 98.3% - Reduction of finishing time from 5 minutes to 1 minute. - Changing the production bottleneck from the printing stage to the assembly stage.
Supply Chain	- 1 day delivery time. - Production of parts on demand. - Shortening the links in the supply chain, direct production to the customer.

5 FINAL CONSIDERATIONS AND CONCLUSIONS

Due to the pandemic installed by COVID-19, the Open Laboratory of Brasília (LAB) of the University of Brasília (UnB) was requested to produce a face shield, a medical device. The initial challenge of the project was to deliver a face shield for use in a hospital environment, in which the customer was not willing to wait for the product to be developed. That is, the demand was for a ready-to-use product.

Based on customer feedback and the problems identified in production, supported by the integration of lean philosophy with DfAM. Changes in design and manufacturing were quickly implemented, about a day.

Through the use of action research methodology, the team involved absorbed the methods and tools of the Lean philosophy approach and DfAM, understanding the reasons for decision-making throughout the project.

Due to the urgency and emergency, most of the product and process data and controls were performed traditionally. However, it is noteworthy that the data modeling was carried out to provide subsidies for future projects.

The AM technology needs to be integrated with other technologies of Industry 4.0, to reach its full potential. However, the LM methods and tools used were sufficient to maintain the quality of the face shields and support the stability of the manufacturing process.

The expected results were achieved, due to the commitment, engagement of the project team, and the application of LM principles. The results regarding the benefits of AM, it is inferred the importance of LM for adopting AM to produce final product parts, mainly for the implementation of strategies to reduce the supply logistics chain and meet the demand for products closer to the client.

Continuing the research involves digitizing the services provided through the production of parts produced by Additive Manufacturing at the LAB, allowing the creation of a simulation environment for the training of undergraduate and graduate students.

ACKNOWLEDGMENTS

We thank all those, directly and indirectly, involved in the project *Producão Vida 2020*. This project was financed by the *Fundação de Apoio do Distrito Federal* (FAP/DF) under agreement No. 03/2020, aimed at combating COVID-19, with aid of *Fundação de Empreendimentos Científicos e Tecnológicos* (FINATEC).

This project received additional financial resources from the Brazilian Labor Public Ministry.

REFERENCES

AGÊNCIA NACIONAL DE VIGILÂNCIA SANITÁRIA. Resolução – RDC n. 356, de 23 de março de 2020. 2020. Disponível em: http://www.in.gov.br/en/web/dou/-/resolucao-rdc-n356-de-23-de-marco-de-2020-249317437. Acesso em: 23 mar. 2020.

BELTRAMI, M., ORZES, G. Additive manufacturing applications perspectives in small and medium enterprises. Natural Science, n.2, 2021. DOI:10.12982/CMUJNS.2021.024

BIAZZO, S.; PANIZZOLO, R.; GORE, A. Lean product development implementation approach: empirical evidence from Indian lean manufacturing. International Journal of Industrial Engineering and Management. v.8, n.3, p.189-201, 2017.

BOYARD, N. et al. A design methodology for parts using additive manufacturing. In: 6TH INTERNATIONAL CONFERENCE ON ADVANCED RESEARCH IN VIRTUAL AND RAPID PROTOTYPING. [S.l.: s.n.], 2014. p. 399–404.

GARCÍA-DOMINGUEZ, A., CLAVER, J., SEBASTIAN, M. A. Integrating additive manufacturing, parametric design, and optimization of parts obtained by fused deposition modeling (FDM). A methodological approach. Polymers Multidisciplinary, v. 12, n.9, p.1933, 2020.

GHADGE, A. et al. Impact of additive manufacturing on aircraft supply chain performance: A system dynamics approach. Journal of Manufacturing Technology Management, v. 29, n. 5, p. 846-865, 2018.

GHODADIAN, A. et al. Examining legitimatization of additive manufacturing in the interplay between innovation, lean manufacturing, and sustainability. International Journal of Production Economics. p.457-468 2018. DOI: 10.1016/j.iijpe.2018.06.001

KUMKE, M., WATSCHKE, H., VIETOR, T. A new methodological framework for design for additive manufacturing. Virtual and Physical Prototyping, v. 11, n. 1, p. 3–19, 2016.

LI, L. et al. Multi-view feature modeling for design for additive manufacturing. Advanced Engineering Informatics. v. 39, p. 144-156, 2019.

LIU, P. et al. The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (SCOR) model-based analysis. Production planning & control. v. 25, p. 13-14., 2014.

OETTMEIER, K.; HOFMANN, E. Impact of additive manufacturing technology adoption on supply chain management processes and components. Journal of Manufacturing Technology Management, v. 27, n. 7, p. 944-968, 2016.

OLSEN, T. L.; TOMLIN, B. Industry opportunities and challenges for operations management. Manufacturing e-Service Operations Management. v.22, p.113-122, 2020.

OPPENHEIM, B. Lean product development flow. Systems Engineering, v.7, n.4, p.352-376, 2004.

PAGLIOSA, M.; TORTORELLA, G.; FERREIRA, J. C. E. Industry 4.0 and lean manufacturing. Journal of Manufacturing Technology Management. v.32, n.3, p. 543-569, 2021.

PONCHE, R. et al. A new global approach to design for additive manufacturing: A method to obtain a design that meets specifications while optimizing a given additive manufacturing process is presented in this paper. Virtual and Physical Prototyping, v. 7, n. 2, p. 93–105, 2012.

PRADEL, P. et al. A framework for mapping design for additive manufacturing knowledge for industrial and product design, Journal of Engineering Design, v.29, n. 6, p.291-326, 2018

PRUSA 3D. Printed face shields for medics and professionals. Disponível em http://www.prusa3d.com/covid19. Acesso: 20 de abr. 2020.

ROSSO, S. et al. An optimization workflow in design for additive manufacturing. Applied Sciences, v.11, 2021. DOI: 10.3390/app110662572.

SILVA, P. C. et al. Manufatura Aditiva: Revisão Sistemática da Literatura. Brazilian Journal of Development. Curitiba, v.6, n.11, p. 84502-84515, nov. 2020.

TAREQ, M. S. et al. Additive manufacturing and the COVID-19 challenges: An in-depth study. Journal of Manufacturing Systems, v. 1, 2021. DOI: 10.1016/j.jmsy.2020.12.021.

THOMPSON, M. K. et al. Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP Annual -Manufacturing Technology, v. 65, p.737–760. 2016,

VOLPATO, N. (Org.). Manufatura Aditiva e aplicação da Impressão 3D. São Paulo: Blucher. 2017.

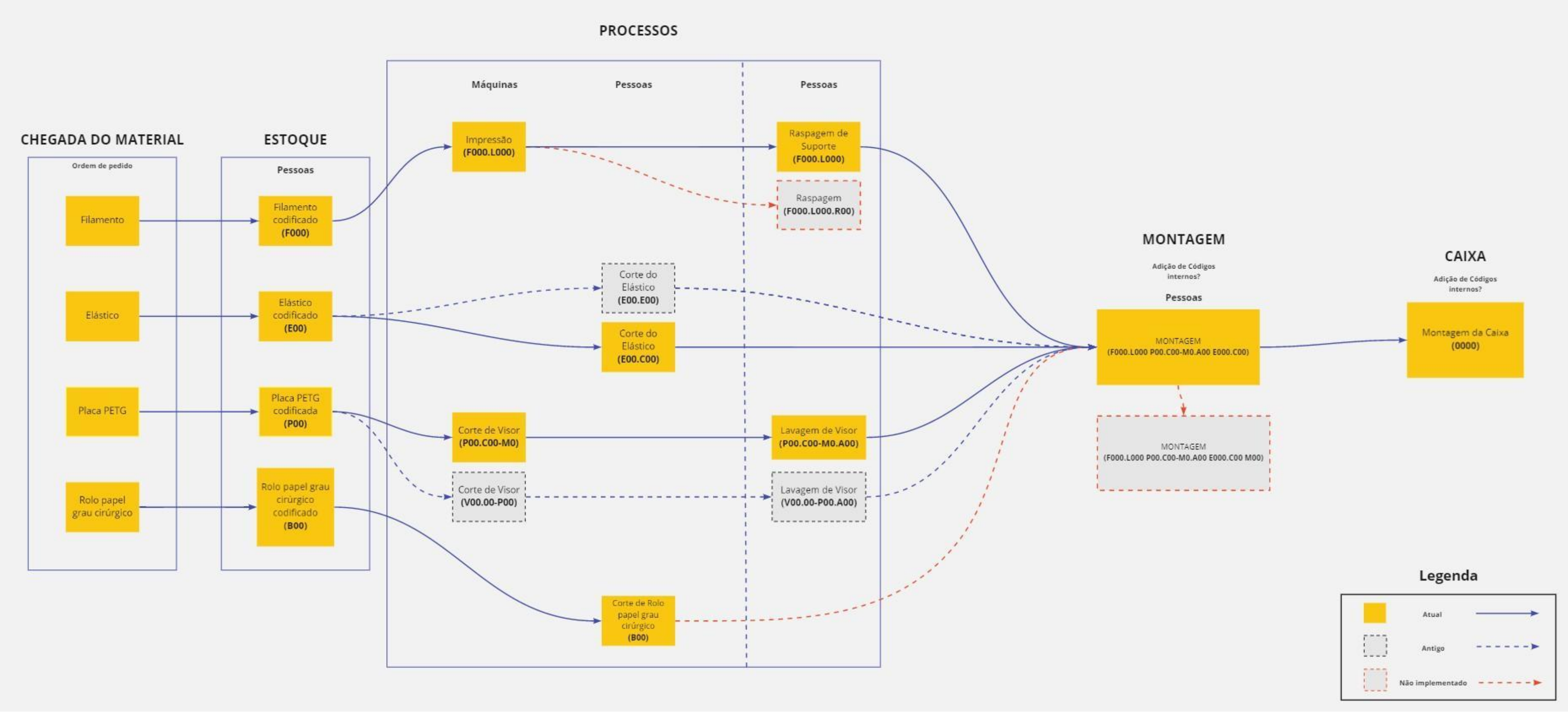
WOMACK, J. P.; JONES, D. T. Lean consumption. Harward Business Review, v.83, n.3, p.58-68, 2005.

YANG, S. et al. Towards an automated decision support system for the identification of additive manufacturing part candidates. Journal of Intelligent Manufacturing. v.31, p.1917-1933.

ZHU, Y. et al. An Improved density-based design method of additive manufacturing fabricated inhomogeneous cellular-solid structures. International Journal of Precision Engineering and Manufacturing. v.21, n.1, p. 103-116, 2020.

ISSN: 2525-8761

APPENDIX A – Item traceability



Fonte: LAB Archive (2020)