

COLLABORATIVE PROJECT AS A DIDACTIC PLATFORM OF VIRTUAL MOBILITY FOR ADDITIVE MANUFACTURING COURSE

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Abstract: Industry 4.0 refers to new production methods to meet current societal challenges, notably the improvement of working conditions and the optimization of flows with remote process monitoring. It requires engineering schools to be able to train in new transversal skills. This article presents the experience on international virtual mobility with a Brazilian (UFRJ) and a French (INSA Toulouse) School of Engineering in the area of additive manufacturing. The objective was to develop a collaborative project in distance with a defined technical objective. The project was conducted with weekly meetings during the scheduled classes. An extruder to produce FDM filaments was installed in INSA Toulouse by the French students advised by the Brazilian students, which allowed the production of poly(lactic acid) - PLA/carbon fiber composite filaments. Specimens for mechanical resistance tests and 3D workpieces were designed and FDM printed using the produced filament. The project required multidisciplinary profiles and planning, organizing, and communication skills. As a result, both technical results and educational challenges are presented.

Keywords: Industry 4.0, Internacional Virtual Mobility, Additive Manufacturing, FDM, Composite filament.)

1. INTRODUCTION

The additive manufacturing (AM) is a recent manufacturing process that has been growing up the last 10 years and it is getting to production scale (Campos *et al.*, 2020). Its inclusion in Engineering courses is mandatory due to the technological contribution that this concept causes to workpiece design, to the development of new materials (Coelho *et al.*, 2019) and to adapt the industrial chain as it is one of the nine technological pillars of Industry 4.0 (Motyl *et al.*, 2017).

There is a needed for the development of Industrial Internet of Things in the Engineering course (Louw and Deacon, 2020) with a strong basis of manufacturing processes. "Modern manufacturing education plays a key role in preparing qualifies workforce for the manufacturing industry", as claimed Ngaile *et al.* (2015) detailing that they need new innovation, technologies and customer-driven products.

Motyl and Filippi (2021) discussed about the educational strategies adopted at university level that involve AM. They made a cartography of 30 articles in journals and conferences that studied this topic and they claimed that "what emerges is a strong interest in improving the education of engineering students through the introduction of courses or workshops dedicated to Industry 4.0 subjects, in particular to manufacturing improvement and to the use and deepening of AM techniques for production. (...) and the need to introduce new skills."

The classical way for inclusion of a new process in the curriculum is to add a topic in the current course of "Introduction to Manufacturing Processes" (Groover, 2014), to create optional courses of the new thematic and to promote the thematic in the final engineering project subjects (Coelho, 2016; Gutnik, 2017). Although, the changes that this process causes to the way of designing parts and assembly mechanisms, should include the interdisciplinary in Industrial Engineering, as mechanical design and metrology in order to impact the development of a specialized profile (Ngaile *et al.*, 2015).

The new curriculum should include the classical FDM (Fused Deposition Modeling) process, the most economic AM process, but also the other AM strategies, as powder bed (SLS, SLM), selective powder deposition and photo-curing polymers (SLA) process (Magaldi *et al.*, 2018). It should provide discussing about what process will be more adapted to

each project and material, as shown by Diegel *et al.* (2019) and Flores Ituarte *et al.* (2019).

Havenga and Swart (2022) proposed an problem-based (active learning) course in the first year of Engineering for cooperation in real word projects. This article claims that the student works together solving multidisciplinary Engineering problems developing inquiry, critical dialog, creative thinking and active participation. In INSA Toulouse, the first year has a common curriculum for all Engineering courses with an specific module that includes AM in first year: the students should design a small piece (printing time under 25 min) in CAD software and send it to the 3D printers. This activity was chosen to fit on the available time of the students in one of the two practical manufacturing classes. So, adding this activity to the last year of Engineering could use the knowledge that they developed in the five years of Engineering and explore more possibilities of collaboration inside the group. On the contrary, students of Materials engineering and Metallurgical Engineering courses in UFRJ only take contact with additive manufacturing techniques when they decided to develop final projects or training activities within specific research groups of the Department that work with these techniques. Up to now, there is no specific (elective or compulsory) subject within their academic curriculum related to this topic.

In order to overcome these academic gaps, we conducted a virtual project course in additive manufacturing for a group composed of three students from the fifth-year of mechanical engineering students in a French Institution (INSA-Toulouse) and four fourth-year students from Metallurgical Engineering and Materials Engineering in a Brazilian University (UFRJ). This original educational approach aimed to bring together students from different establishments in the form of virtual meetings to build a mechanical project with an online manufacturing workshop. The target of the project was partially defined by the professors who guided through deadlines and technical suggestions.

The objective of this article is to share the experience of this course and motivate professors to introduce actual tools that prepare our Engineers for the international connected industries developing soft skills of: integration from different scientific fields, multicultural communication and contributing to the practice of the technical English language in a professional situation.

The structure of this article includes: the virtual mobility proposition to the partners, the organization before the course, the description of the students internal organization inside the group, a brief overview of the technical development and its results, and, in the last section, the pedagogical results and conclusions.

2. COURSE ORGANIZATION WITH PARTNERS

The program of the standard “Advanced additive manufacturing” module at INSA-Toulouse is currently presented in the format: a lecture introducing the main additive manufacturing processes and a review of the process basics, three courses in "conference" format presented by two manufacturers and by a researcher in the field and, then, 7 weeks of experimental and supervised projects in groups of 5 students. The last session will be devoted to project presentations by all groups, including the presentations related to this project that will be done by video-conference for class.

The inclusion of the virtual mobility in this course was gradual : in the first year of implementation, the classes were developed from October 2020 to January 2021 between INSA-Toulouse and Università di Trento supported by a project entitled “3Di Project - Teaching the industry of the future through international monitoring of the FDM additive manufacturing process”. The objective was to create a hybrid course with teaching mobility when manufacturing could be done in both countries. The aim of the project was to reproduce a small structure of a multinational industry with two plants and one common project.

This project was submitted in 2019 (before COVID-19 crisis) for financial support inside the call “IDEFI DEFI Diversités 2020”¹ from Toulouse University to adapt teaching practices to the diversity of student populations. The common actions carried out by this project aim to develop the skills expected by the socioeconomic world.

The financial support for this project was approved in 2020, when the physical part of the collaboration could not be developed due to the mobility limitation due to the lock-down. The first exercise was entirely virtual for the development of the mechanical design, although the final manufacturing could be completed in each country, producing two products: one in Italy and in France.

In this new 2021 version, the objective was to include a third partner: one university in South America without physical student mobility, enlarging the collaboration and repeating the experience. In 2021, two groups from the French class should interact with Italian students and one group with the Brazilian students, activity described in this article. In the case of French-Brazilian group, an adaptation of pedagogic method was necessary, since due to the restrictions imposed by the Covid-19 pandemic, the Brazilian students were not able to carry out the course activities in person at UFRJ, such as Italian students did in the first version.

The academic and industrial lectures were available on an open Moodle platform (Open Insa²) or it was developed with synchronous meetings using Zoom Software so that it could be open to other establishments. The main objective provided for this group was: “Develop challenge activity with a final target product that uses an extruder to produce your own polymer filament”.

The students should carry out the project in 7 sections:

- Section 1: Presentation videoconference and Brainstorming between international students
- Section 2: Definition of the goals of the project and discovery of the new equipment

¹<https://www.univ-toulouse.fr/des-formations-pour-tous/idefi-defi-diversites>

²<https://open.insa-toulouse.fr/>

- Section 3: Presentation of extrusion results for the supervisors
- Section 4: Improvement of the experimental part (corrections and progresses)
- Section 5: Printing of the final product
- Section 6: Elaboration of the presentation of the project results
- Section 7: Presentation of the project online to the three institutions, including the students that do not participate in the project in INSA-Toulouse.

The expected benefits of the project were related to the learning of students in the field of manufacturing and remote monitoring, the international interaction of trainers and students and the dissemination of partnership to other students who are not in mobility.

3. INTERNAL ORGANIZATION

3.1 Internal meeting and organization of the responsibilities

The students defined the title “FDM analysis on the change of mechanical properties of PLA”, the demand (or the specific challenge) as “3D-printed bicycle storage support” and the technical objective to achieve : “Increase the Young’s modulus of the material and increase the maximum stresses” comparing the regular filament with a new proposed one, manufactured by their own experience. As both institutions explained the target, students from both institutions understood the same objective, although each side had specific methodology for practical courses.

In the beginning, even after defining their own way of communication and registering the information, the main fail on the synchronization of progress was related to the difference between the core of the activities: the French students having the practical difficulties onsite and the Brazilian students trying to be useful and define their responsibilities, but online, far from the problem. At this point it was very important to insist that they would have to define each student’s responsibility and that the grade will depend on the homogeneity of the work. The mechanical engineering students had practical extrusion problems that the Brazilian students had the answers and the skill to be able to guide to the solutions. The professors tried to guide and identify the mechanics of the group collaboration and after this point, they were able to develop a structured project with more information flow. The students will be faced with a similar situation in an international company with technological transfer.

The Brazilian group described in their report: *“Furthermore, as a secondary objective, but no less important, we should develop interpersonal skills, which would encompass both the normal difficulties of a multidisciplinary project - in this case, materials, metallurgical and mechanical engineering - as well as the problems of online interaction between students from different cultures in different time zones, communicating in a language other than their mother tongue. (...) we realized throughout the course that we could merge our knowledge in order to seek the best development of the project, even in topics that were a little outside our area.”*

3.2 Analysis of the materials and equipments

The students were free to choose the material for manufacturing the filament. They could use recycled pieces, commercial filaments or polymer pellets. In the beginning of the project, they started evaluating the possibility of producing a filament with magnetic properties. This idea was a cutting edge proposition but they realised that there were practical experimental problems related to a new good idea, what gave them the insight of what could be done in a RD department.

Finally they chose to produce a composite filament with theoretical higher rigidity in order to produce a bicycle support that needs a higher strength. A composite filament with PLA matrix, widely used in 3D printing and available on stock, reinforced by fibers. We had two fibers available on laboratory stock, as we work with aerospace research: glass and carbon fibers. Both materials have a high Young modulus but they decided that carbon fiber offered fewer risks in terms of safety while handling it. This shows that they understood that several components for decision making in Industry Industry should be considered.

The available equipment for the project included an extrusion filament equipment (Filafab 3D3) with Spool Winder (FilaFab Mk3) and a dedicated FDM printer (Ender 3), so there was no impact on other projects. The equipment can be seen in Figure 1.

The produced filament was used to print samples for tensile tests with dog-bone shape type V (ASTM D638-10 Standard). Five workpiece of each condition were printed. Table 1 shows some experimental parameters used to produce the PLA/carbon fibers filaments and printed parts.

3.3 Theoretical material behavior

The theoretical background of the students is linked to elastic behavior of homogeneous material to simulate the mechanical behavior of composites. They did not consider other parameters, for example, friction forces and temperature in the extrusion head and its effects.



Figure 1: Equipment available exclusively for the group (Extruder, winder and filament stocking) and FDM printer.

Processes	Parameters
Extrusion	Barrel temperature = $187^{\circ}C$ Screw speed = 3 rpm Winder-extruder distance = 15 cm
3D printing	Printing speed = 35 mm/s Nozzle temperature = $200^{\circ}C$ Bed temperature = $60^{\circ}C$ Infill density = 100% Raster angle = $\pm 45^{\circ}$

Table 1: Parameters used to produce filaments and printed parts

The students predicted the elasticity modulus using the Young modulus of each composite material. The students used the properties values from the literature (approximate values). According to Zweben and Beaumont (2017), the theoretical Young modulus of carbon fiber is between about 35-1000 GPa, depending on fiber orientation (along the axial axis or layer plane). They used the average of 517 GPa for fibers and between 3-4 GPa for PLA, based on a comparative study (Santana *et al.*, 2018). Regarding the mass ratio, they chosen 1 wt% and 5 wt% fiber after consulting some commercial websites.

They chose two models for calculating the composite rigidity:

1. **Krenchel model:** based on the mixing rule, including an experimental factor η related to the orientation of the fibers inside the matrix. They used $\eta = 3/8$, because it is the value for random fibers and homogeneously distributed in the lamina.

The composite elastic module E_c based on Krenchel model is dependant on the elastic modulus of the matrix E_M and the fibers E_F and also its volumetric ratio V_M and V_F :

$$E_c = E_M V_M + \eta E_F V_F \quad (1)$$

2. **Halpin-Tsai Model:** It is used to predict elastic properties of the material based on an empirical model. It presents an efficiency factor ξ related to the length of the fibers l_F and its diameter d_F : $\xi = \frac{2l_F}{d_F}$. And a factor η that relates the behavior of the elastic properties of the matrix and the fiber, as the previous model.

Eq. (2) presents the composite elastic module E_c calculation using this model:

$$E_c = E_M \left(\frac{1 + \xi \eta V_F}{1 - \eta V_F} \right) \quad (2)$$

The theoretical values obtained, respectively, are 5.44 GPa and 5.73 GPa, considering 1 wt% of carbon fiber. It is important to highlight that these are theoretical results, which means that every mathematical model has approximations. For instance, the Krenchel model presuppose that the fibers are homogeneously and randomly distributed. So, in this model, the fiber orientation and distribution play an important role when the elastic property is calculated. On the other hand, the Halpin-Tsai is an empirical model that can foresee satisfactorily if the fibers are well oriented in the main loading direction. Once again, the fibers orientation plays decisive role.

3.4 Manufacturing workpieces and mechanical tests

Figure 2 presents some images of the three experimental parts of their work: the filament production (with and without fibers), the specimen manufactured by FDM and the tensile tests.

The students faced some experimental problems:

- The extruder was quite small, without any technical after sales service. So, the students in France faced a lot of problems to regulate the flow and to achieve a constant diameter of the filament. Therefore, the single screw

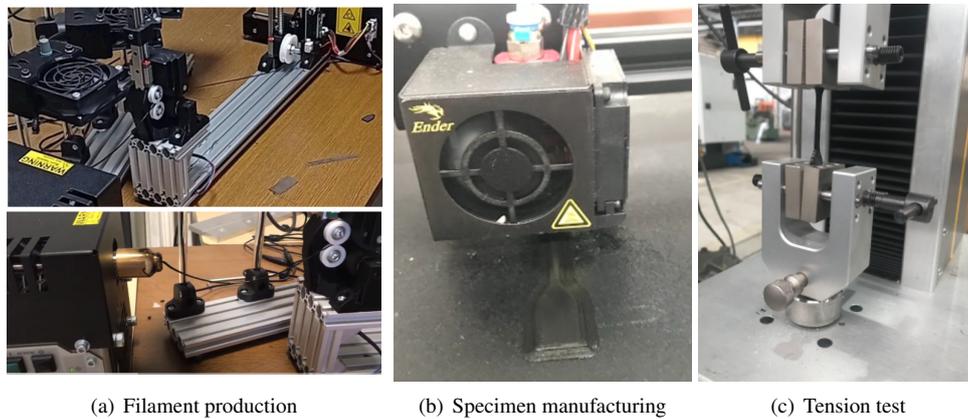


Figure 2: **Manufacturing and Test Sequence.**

extruder does not reach high values of pressure and shear rate, which impaired the production of a composite. As a solution, the students proposed a low volume fraction of the reinforcement fibers and/or to increase the extrusion temperature to improve the fluidity of the polymer, although this increasing could led to the degradation of PLA molecules.

- In the beginning, they observed that the pure PLA filament produced using polymer pellets was getting thin and brittle. They decided to use cut pieces of a PLA commercial filament as raw material for extrusion process instead of polymer granules in order to benefit of the additives the industry includes in their products. . The cooling process of the extruded filament was also evaluated. They proposed to change the cooling based on the theoretic basis on polymer behavior. The filament was cooled in air.
- Adding carbon fiber to the PLA, they had the difficulty to separate the fibers and mixing it in a homogeneous way inside the container of the extruder, before the hot channel. To overcome this problem, they reduced the cut pieces of FDM filament to improve mixture capability, and then, mixed with carbon fibers before feeding the extruder.
- For the printing stage, they realize that the printing parts with home produced filament should take into account the diameter they achieved in extrusion: space between layers should compensate the filaments diameter (smaller than expected). The 3D printer was setup for filaments with 1.75 mm in diameter. However, thinner filaments (1.4 mm in diameter) were produced. Thus, students realized that an adjustment in machine was necessary to avoid under-extrusion during printing process. They adapted the FDM parameters to be able to produce the additive manufacturing pieces (bed temperature, nozzle temperature, speed and printing trajectory). Since a large difference between the maximum stresses values was observed, the printing speed were changed to improve the adhesion between the layers.

Figure 3 shows the stress-strain curves of the printed workpieces produced using extruded filaments with and without fibers. According to these results, the incorporation of fibers did not increase the Young modulus. Moreover, composite parts presented lower ductility. The average value of Young Modulus for the composite samples was 2.2 GPa, which is lower than those of the pure PLA. The results obtained by the theoretical models are not comparable to those obtained experimentally, , mainly because the carbon fibers probably agglomerated throughout the filament extruded. One justification could be that the maximum extruder's shear rate was not enough to promote a proper distribution of the filler, which could weaken the samples by creating regions of tension concentration.

3.5 Final presentation and report

In the end of the semester, an online presentation for the other students of this course (other groups not in virtual mobility) and for the professors from France, Brazil and Italy, as it can be observed in Fig. 4. Also, they produced one poster for the evaluation in INSA Toulouse (Fig.4b) and one report in Portuguese for their evaluation in Brazil (Fig.4c).

4. CONCLUSIONS

Clearly, the experimental processing should be improved to obtain better technical results. However, it should be highlighted that the objective of this work was not to explore the technical results, but to show that in course hours the students were able to overcome several difficulties and were successful in producing pure PLA and PLA/carbon fiber filaments by extrusion, 3D printing workpieces from these filaments and analyzing samples by tensile tests. Definitely, in a research exercise, the process should be improved with more regular filaments and understanding why the composite samples was less rigid. For further studies, the student also suggested to study of the effect of printing parameters on the adhesion between the layers and to evaluate the influence of the infill density on the produced composite 3D-printed parts.

The Additive Manufacturing module responds perfectly to the needs of Industry 4.0, by training engineers capable of improving manufacturing performance thanks to their multidisciplinary skills in industrial engineering, materials

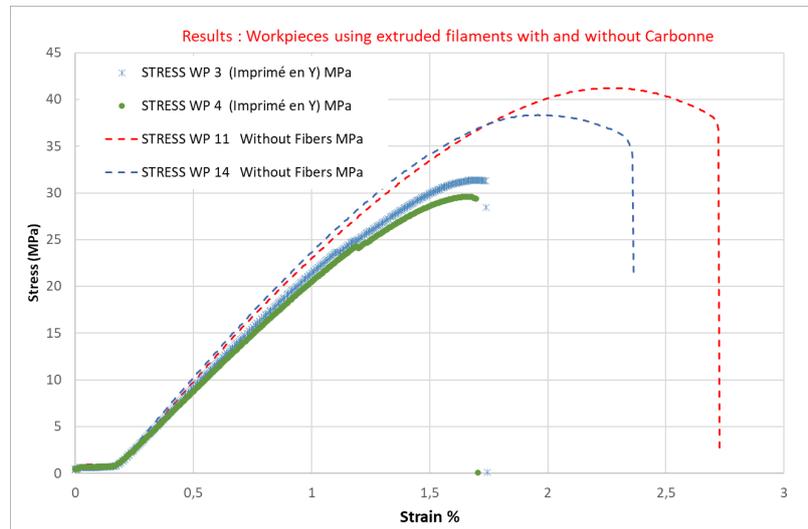


Figure 3: Comparison of mechanical behavior between some samples with and without carbon fibers.

sciences, online connectivity and data analysis, and by reinforcing their transversal skills such as intercultural communication, teamwork and creativity. Thanks to the pedagogical approach (problem-based learning) and the hybrid format, students will be directly confronted with problem solving in real situations in manufacturing and worked in an international multidisciplinary team.

5. ACKNOWLEDGMENTS

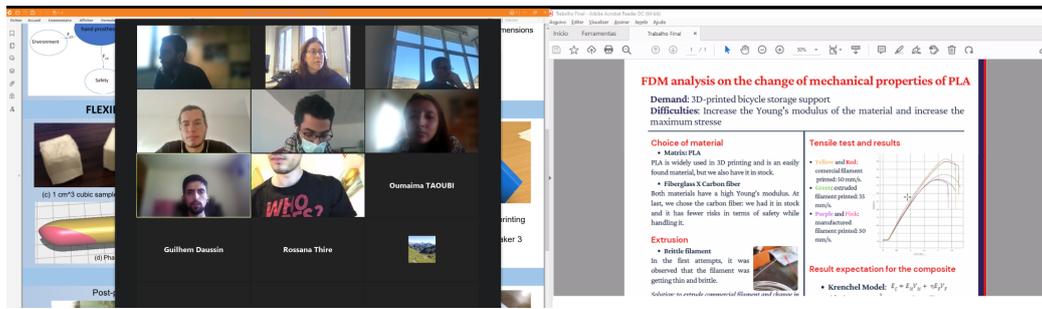
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6. RESPONSABILIDADE AUTORAIS

O(s) autor(es) é(são) o(s) único(s) responsável(is) pelo conteúdo deste trabalho.

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(a) Project defense online

FDM analysis on the change of mechanical properties of PLA

Demand: 3D-printed bicycle storage support
Difficulties: Increase the Young's modulus of the material and increase the maximum stress

Choice of material

- **Matrix: PLA**
PLA is widely used in 3D printing and is an easily found material, but we also have it in stock.
- **Fiberglass X Carbon fiber**
Both materials have a high Young's modulus. At last, we chose the carbon fiber: we had it in stock and it has fewer risks in terms of safety while handling it.

Extrusion

- **Brittle filament**
In the first attempts, it was observed that the filament was getting thin and brittle.
Solution: to extrude commercial filament and change in cooling.
- **PLA + carbon fiber**
Difficulty in separating carbon fibers and mixing.
Solution: to reduce their sizes in order to improve mixture capability.

3D printing

- **Spacing between layers**
The diameter of one of the filaments was smaller than expected and the printer settings were not changed. Thus, it probably occurred subextrusion.
Solution: To change the settings.
- **Printing speed reduction**
Since a large difference between the maximum stresses values was observed, the printing speed were changed to improve the adhesion between the layers.

Tensile test and results

- **Yellow and Red:** commercial filament printed: 50 mm/s
- **Green:** extruded filament printed: 35 mm/s
- **Purple and Pink:** manufactured filament printed: 50 mm/s

Result expectation for the composite

- **Krenchel Model:** $E_c = E_m V_m + \eta E_f V_f$
Considering: $\eta = \frac{2\xi}{d} \rightarrow$ random fibers evenly distributed.
 $E_c \approx 5,44 \text{ GPa}$
- **Halpin-Tsai Model:** $E_c = E_m \left(\frac{1 + \xi \eta V_f}{1 - \eta V_f} \right)$
Considering: $\xi = \frac{2l}{d}$ and $\eta = \frac{(E_f/E_m) - 1}{(E_f/E_m) + 1}$
 $E_c \approx 5,72 \text{ GPa}$

Opportunities for future projects

- Print the product and do the tests to evaluate the mechanical performance:
- Study of the adhesion between the layers of the composite.
- Evaluation of the influence of the density of the polymer formed on its properties.

Logos for INSA Toulouse, Politécnica UFRJ, and project team members: Atlas Rais, Leo Sudries, Tom Gaboriaud, Giovanna Siqueira, Raphael Ertola, Vitor Corrêa.

(b) Final poster for INSA Toulouse

Logos for METALMAT and Politécnica UFRJ.

Brasil - França
RELATÓRIO FINAL:
MANUFATURA ADITIVA

Giovanna Siqueira, Raphael Ertola e Vitor Corrêa

(c) Final report for UFRJ

Figure 4: Final presentation and reports

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MOBILIDADE VIRTUAL COMO FERRAMENTA DIDÁTICA PARA DESENVOLVIMENTO DE COMPETÊNCIA DE COLABORAÇÃO EM PROJETO DE FABRICAÇÃO ADITIVA

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Resumo: A Indústria 4.0 refere-se a novos métodos de produção para atender aos atuais desafios da sociedade, em especial a melhoria das condições de trabalho e a otimização de fluxos com monitoramento remoto de processos. Requer que as escolas de engenharia sejam capazes de treinar novas habilidades transversais. Este artigo apresenta a experiência de mobilidade virtual internacional com uma escola de engenharia brasileira (UFRJ) e francesa (INSA Toulouse) na área de manufatura aditiva. O objetivo foi desenvolver um projeto colaborativo à distância com um objetivo técnico definido. O projeto foi realizado com encontros semanais durante as aulas programadas. Uma extrusora para produção de filamentos FDM foi instalada no INSA Toulouse pelos estudantes franceses orientados pelos estudantes brasileiros, o que permitiu a produção de filamentos compostos de poli(ácido láctico) - PLA/fibra de carbono. Amostras para testes de resistência mecânica e peças 3D foram projetadas e impressas em FDM usando o filamento produzido. O projeto exigia perfis multidisciplinares e habilidades de planejamento, organização e comunicação. Como resultado, tanto os resultados técnicos quanto os desafios educacionais são apresentados.

Palavras-chave: Indústria 4.0, Mobilidade Virtual Internacional, Manufatura Aditiva, FDM, Filamento Compósito.