Additive Manufacturing in Spare Parts Management in the Maritime Industry

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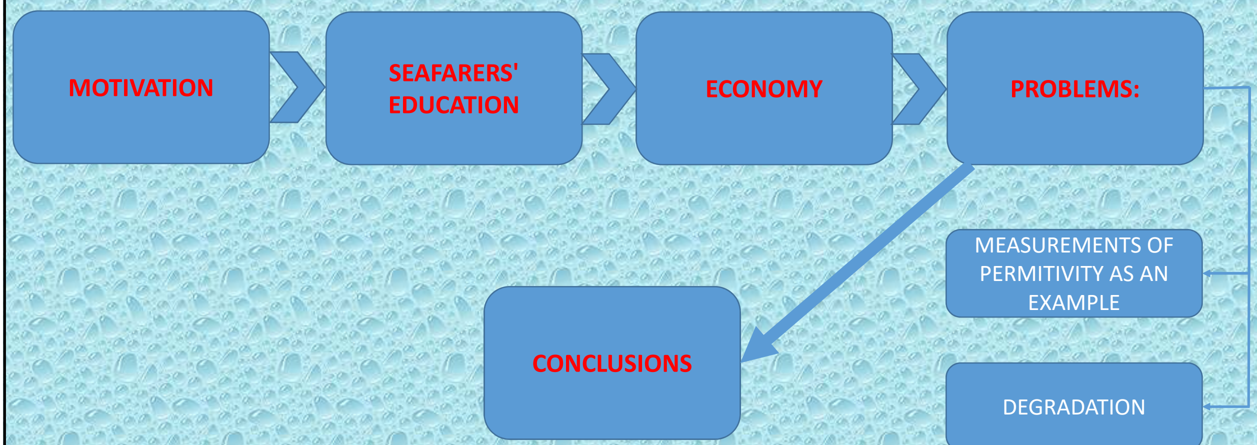
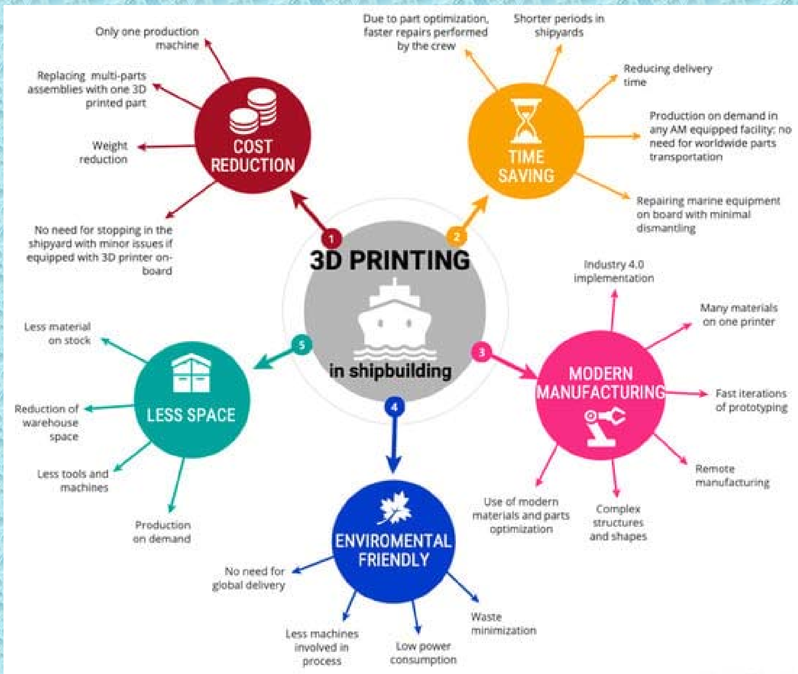
Presentation overview



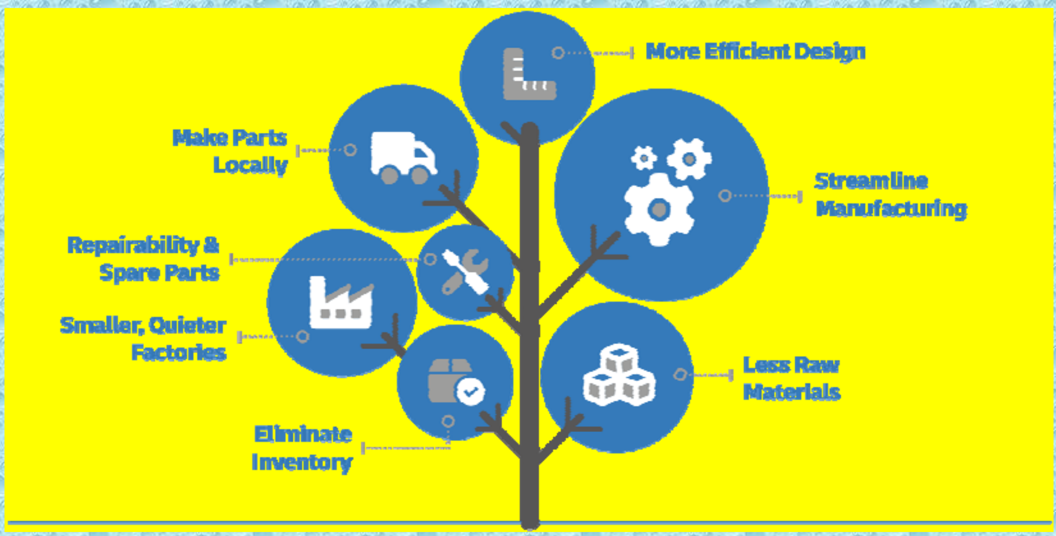
INTRODUCTION

- Motivation in general:

Source: Ziółkowski, M.; Dyl, T. Possible Applications of Additive Manufacturing Technologies in Shipbuilding: A Review. Machines ***2020****, 8, 84. https://doi.org/10.3390/machines8040084*



Introduction – motivation in general



Source: https://www.dhl.com/global-en/home/insights-and-innovation/thought-leadership/trend-reports/3d-printing-logistics.html

INTRODUCTION

Motivation for education:

- New technologies (or not so new, but not included in STCW) should be integrated into education curriculum to cope with advances in technology
- Making educational process more interesting to students
- Better teaching technique: „teaching by doing" – students actual build something
- Informing on new trends and what could be expected in future

Ways to introduce 3D printing in education

- Students' theses and graduate theses
- Change of curriculum by:

Firstly

1) changing a curriculum of existing courses,
2) Implementation of new knowledge through new courses

Example 1 – diploma thesis 1

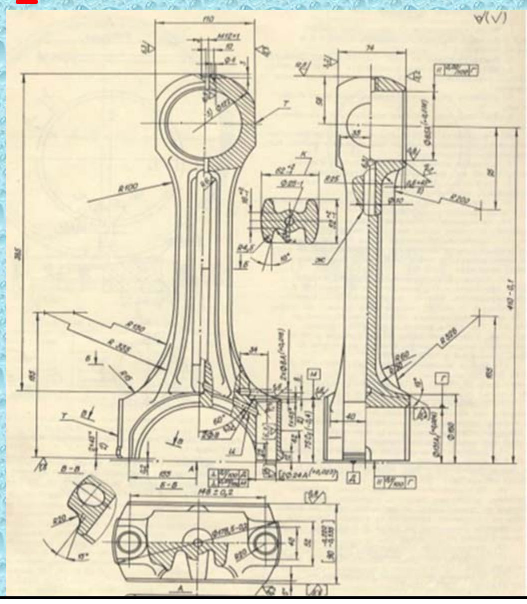
- Neven Maleš, An implementation of 3D printing technology in making models of engine parts, 2018. Advisor: Igor Vujović.

- Construction of 3D printer
- Modeling of the engine part
- Printing the engine part
- Flaw: for real metallic parts of the real engines, appropriate 3D printers are necessary.
- Conclusion: A universal printer for all materials does not exist. Hence, for the aboard ship, we'll need several printers for various materials.

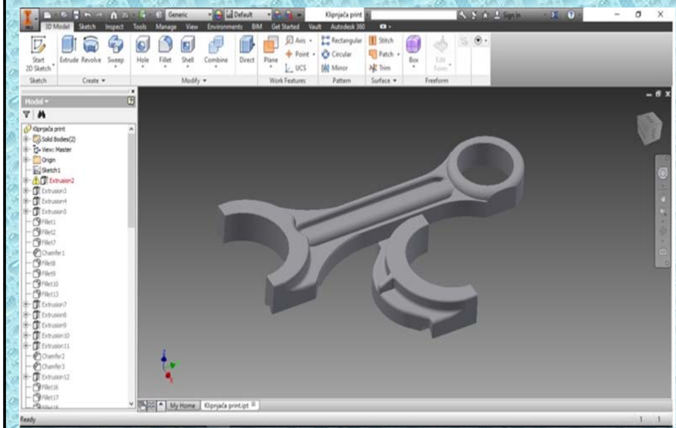
Example 1 – diploma thesis 1

Students' work: constructed 3D printer

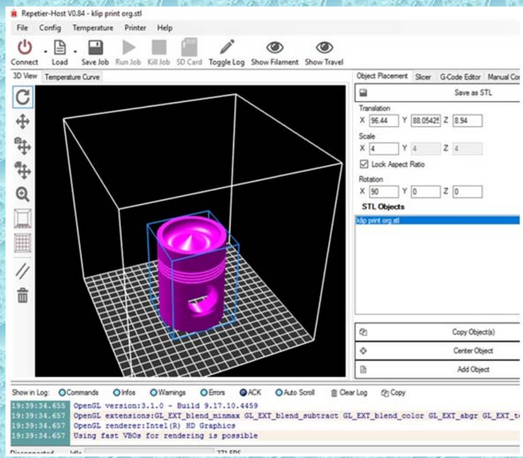
Source for CAD model of the engine connecting rod



Example 1 – diploma thesis 1



Connecting rod model in Autodesk Inventor



Visualization of the appearance and position of the piston model in the Repetier program

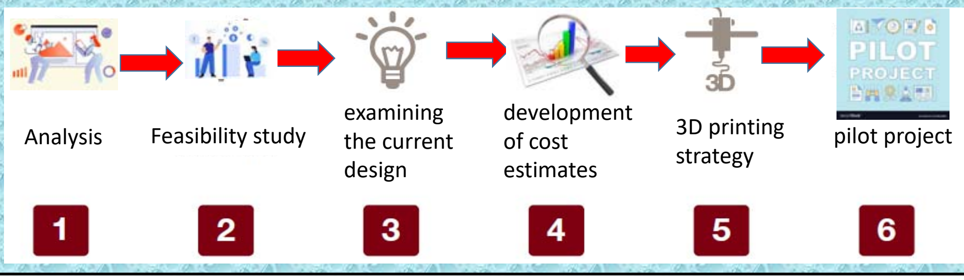
Example 1 – diploma thesis 1

Piston model printed with infill density: 20%, and 35%

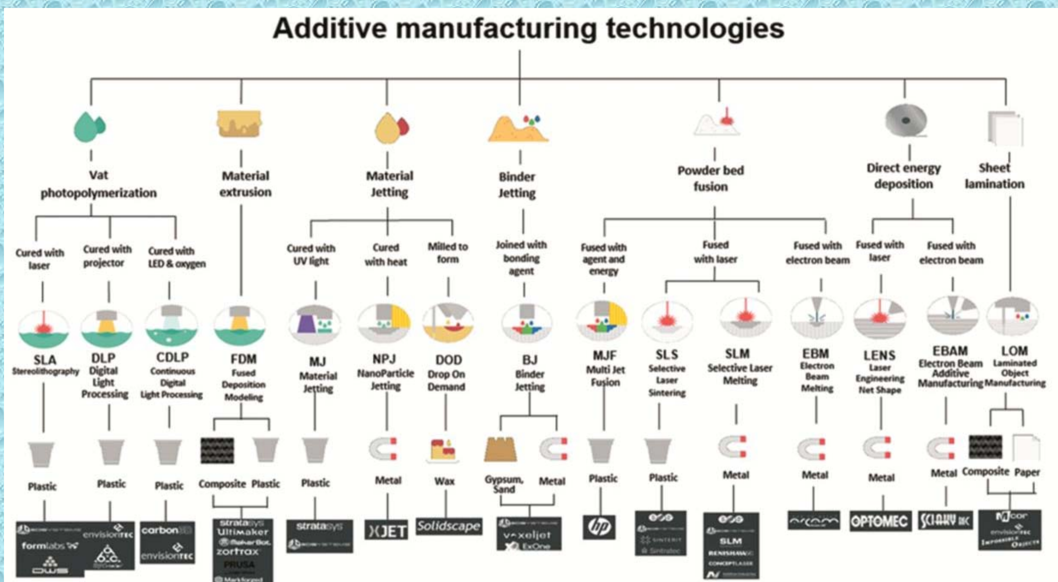
Irregularities on the dome of the eye of the piston

Example 2 – diploma thesis 2

- Vice Terzić, Possibilities of implementation of spare parts 3D printing onboard ships, 2019. Advisor: Igor Vujović.
- Considerations about additive technology
- Process flow
- Cost analysis

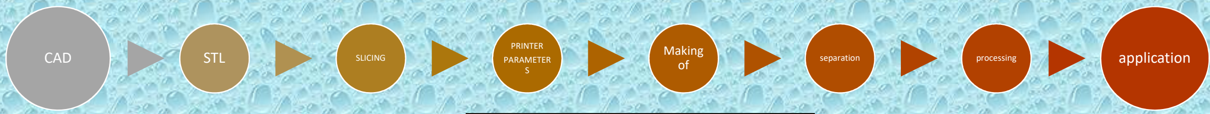


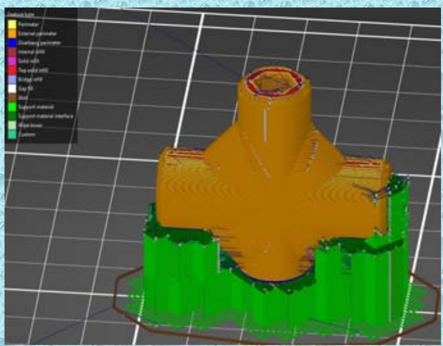
Example 2 – diploma thesis 2



Source: Additive manufacturing of composite materials by FDM technology: A review, http://op.niscpr.res.in/index.php/IJEMS/article/view/45920

Example 2 – diploma thesis 2: 3D models used for results





Slicing

Suport structure

Model made from PLA

Example 2 – diploma thesis 2: models built by FDM (PLA i PETG materials)

Electrical locker key: PLA (white) i PETG (black)

- Quality
- Filling
- Material
- Speed
- Time
- Cooling
- Support
- Stand

Attempting to 3D print a screw

Logical choice for a case study: the key is important and easy to loose!

Example 2 – diploma thesis 2: availability study

MTBF = 822 h, MTTR 8.3 h.

$$A_{no3D} = \frac{822}{822+8.3} = 0.9900036131518728$$

$$A_{with3D} = \frac{822}{822+1} = 0.9987849331713244$$

The difference is 0.87813200194964% !!!

For FAS (engl. *fueling at sea*) control unit, MTBF is 52000 h, and MTTR is 2.1 h. Hence:

$$A_{no3D} = \frac{52000}{52000+2.1} = 0.9999596170154667$$

$$A_{with3D} = \frac{52000}{52000+1} = 0.9999807696005846$$

Which is 0.00211519903793% improvement in availability.

Example 2 – diploma thesis 2: availability study

For the ship lift system with a load capacity of 5443.1 kg MTBF = 17680, and MTTR = 5.6 h.

Hence:

$$A_{no3D} = \frac{17680}{17680+5.6} = 0.9996833582123309$$

$$A_{with3D} = \frac{17680}{17680+1} = 0.99994342113002658$$

Which is only a 0.026% increase in availability.

From the aspect of system availability, there are small differences if the corresponding part was on board, which does not have to be the case. The lower the MTBF, the higher the system's availability with regard to the application of 3D printing technology. However, this is not good, because in this case, the best result would be achieved if a component was constantly under repair, which means that it would not work.

Example 3 – diploma thesis 3

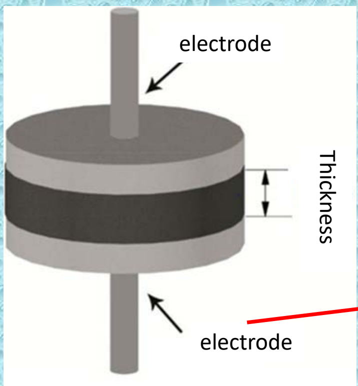
Marin Goltnik, 3D additive technologies of spare parts manufacturing aboard ships, 2020. Advisor: Igor Vujović.

This gear model is a classic example of the strength and power of additive technology and the use of 3D printing with all its advantages.
The gear model is designed in such a way that the internal gears are interconnected by an external circular gear, so the model is similar to the bearings of an electric motor.
The material that was used is certainly not suitable for making bearings, but it can be used very easily to transfer the force of smaller electric motors to a secondary device driven by an electric motor.
The model was made from a single print and subsequently processed to make it mobile and at the same time remain compact as a whole.

Example 3 – diploma thesis 3

- To further analysis of 3D printed product, one electrical property was studies – permittivity.
- It is performed by printing a part and measurement by hole-plate method.

Example 3 – diploma thesis 3



Experimental setup

Hole-plate method

Example 3 – diploma thesis 3

Dielectric constant - the ratio of the capacity of a capacitor with a dielectric material in relation to the capacity of a capacitor without a dielectric material (the capacity of a vacuum equal to 1):

$$\varepsilon = \frac{C}{C_0}$$

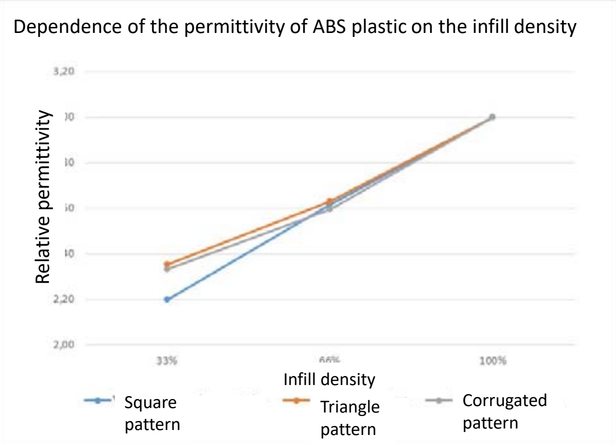
Permittivity is described as the extent to which a particular material interacts in the presence of an electric field and becomes polarized by that field.

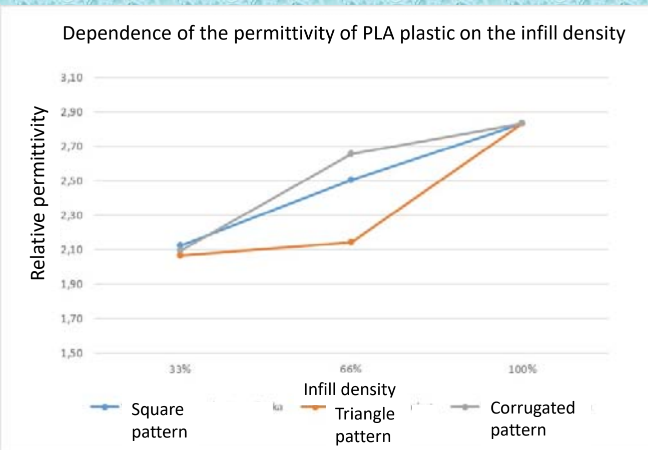
Recall plate capacitor: $C = \varepsilon \frac{A}{d}$

$$\varepsilon_r = \frac{Cd}{\varepsilon_0 A} = C \boxed{\frac{d}{\varepsilon_0 A}} = \frac{C}{C_0}$$

ε_r- relative dielectric constant, permitivity of the media
ε_0- dielectric constant of vacuum ($8.8541878176 \times 10^{-12}$ F/m)
C- capacity of the capacitor (F)
A- the overlapping surface of the capacitor plates (m^2)
d - the distance between capacitor plates (m).

Example 3 – diploma thesis 3: Results





Courses

- Students' theses and graduate theses
- Change of curriculum by:

1) changing a curriculum of existing courses,
2) introduction of new courses

Based on students' theses as statring point.

- New technologies of materials in electrical engineering
- New technologies in diagnostics and control
- Advanced diagnostics and control

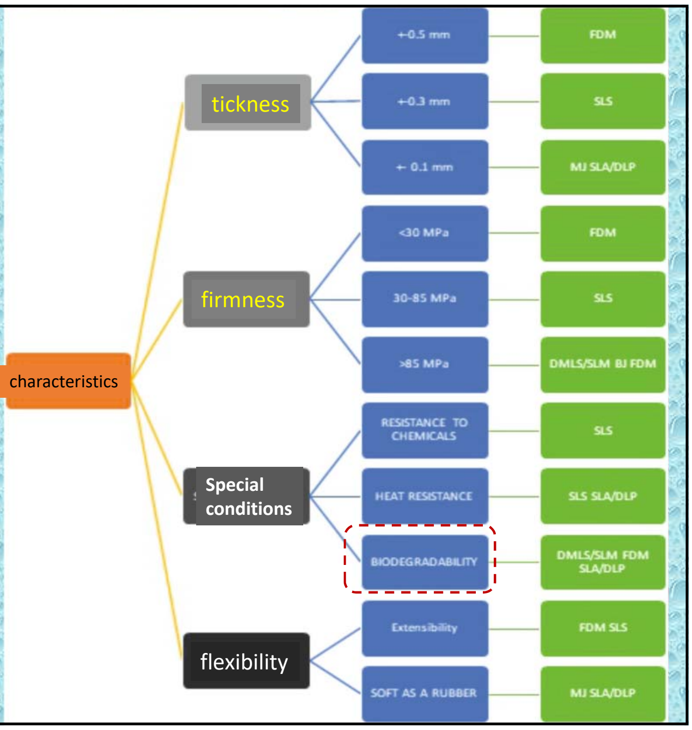
Courses

- Ivica Kuzmanić, Igor Vujović, Zlatan Kulenović, Miro Petković, Introduction Of 3D Printing Into Marine Electrical Engineering Education – A Case Study, Pedagogy, 2021. https://doi.org/10.53656/ped21-6s.23int

- Presented workflow of course program modification is presented.
- Change of curriculum
- Monitoring of students' responds

Economy and sustainability of 3D printing in maritime

Kuzmanić, I., Vujović, I., Terzić, V., Vujović, I. Additive manufacturing in marine engineering education. *Prog Addit Manuf* **7**, 521–530 (2022). https://doi.org/10.1007/s40964-022-00278-7



Economy and sustainability of 3D printing in maritime

- How does the manufacturer arrive at the final price of the product?
- First, the production costs for one product (in our case - one print) are calculated:
- **machine cost (*S*):** electricity consumption, space rental if any, machine depreciation, machine maintenance, consumable parts of the machine (nozzle, base), which gives the price of the machine's working hour
- **material cost (M):** the price of the material used to make the model, which is measured in grams with FDM, while with SLA printing, it is measured in liters, depending on procurement
- **Operator cost (O):** operator’s hourly rate, which includes checking STL files, creating and correcting the file, and preparing the g-code as well as preparing the printer for work: placing materials, cleaning and preparing the substrate, removing the model from the substrate, removing the support material and cleaning and finishing the model; preparing the model for the package and sending it to the end user.

Economy and sustainability of 3D printing in maritime

- **failure cost (N):** considering that the 3D technology is still not 100%, errors occur that result in repeating the entire process, which is added to the previous cost addition and adding 10% of the total sum.

In case of a ship in disaster (need for a spare part), printing failure increases time without it. Hence, the danger is also greater.

- **profit margin (Z):** the margin, the percentage of profit on the manufactured object [Z] is about 140% of the price [C].

In case of a ship in disaster, profit is unnecessary unless the entire system is on lease.

Economy and sustainability of 3D printing in maritime

- Total or final price [U]:

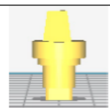
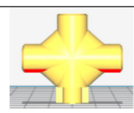
$$[(S + M + O) + N] + C \times 1.4 = U$$

$$C = [(S + M + O) + (S + M + O)\times 0.1]$$

$$[(S + M + O) + (S + M + O)\times 0.1] + [(S + M + O) + (S + M + O)\times 0.1]\times 1.4 = U$$

Economy and sustainability of 3D printing in maritime

Table Price analysis and printing time of the model

PROCESS	MATERIAL	PRODUCT			
		 DIMENSIONS: 16.0x16.0x29.0 mm		 DIMENSIONS: 14.0x44.0x44.0 mm	
*prices are without VAT		Price (in €)	Time	Price (in €)	Time
SLA	ABS	16	75 min	36.13	2.5 h
	ABS+ hot treatment	100	75 min	194	2.5 h
	acrylic resin 100µm	17.33	75 min	36.13	2.5 h
	acrylic resin 150µm	13.33	51 min	26.26	1.7 h
SLS	PA12	41.33	65 min	82.4	2.2 h
	PA12 + glassy particles	41.33	65 min	82.4	2.2 h
3DP	Cast 150	20	20 min	49.6	0.75 h
	starch 15e	33.33	20 min	72.13	0.75 h
FDM (low-budget)	ABS	14	27 min	28.8	1 h
	PLA	13.44	27 min	27.66	1 h
	PETG	14	27 min	28.8	1 h

How to check data?

Statistical analysis was performed to check the data's credibility and conclusions about the relative dielectric constant. There are three parameters. Therefore, the correlation between them was calculated.

Correlation between parameters.

	Printing Time	**Infill Density**	**Material's Length**
Printing time	1		
Infill density	0.8219	1	
The Material's length	0.8517	0.9975	1

How to check data?

An ANOVA analysis between the three observed variables

Source of Variation	F	p-Value	F_{crit}
Between Groups	26228.2	$8.37 \cdot 10^{-41}$	3.402826

Comparison of test parameters for regression and multiple regression.

Regression Type	T	F	P	r^2	$adj\ r^2$
t_p = f(ID)	3.817	14.575	0.0065	0.6755	0.6292
t_p = f(Lm)	4.3	18.496	0.003	0.7254	0.6862
t_p = f(ID, Lm)	N/A *	21.907 **	0.00174	0.8795	0.8394

* available in text for separate variables. ** this is total F. Separate Fs are in the text.

How to check data?

Equation (5) shows the dependence between the dependent variable printing time as a function of the infill densities and material length:

$$t_p = 499.068 - 37.493 \cdot ID + 0.902 \cdot L_m, \quad (5)$$

where t_p is the printing time, ID denotes the infill density, and L_m denotes the material's length.

From Equation (5), it can be seen the variable ID has a negative coefficient, while the variable L_m has a positive coefficient (see again t 2). Also, the variable ID has a stronger influence than the variable L_m. Furthermore, to determine how much data can be explained with Equation (5), the coefficient of determination (r^2), and the adjusted coefficient of determination ($adj\ r^2$) metrics were calculated. From data $r^2 = 0.8795$ and $adj\ r^2$ is equal to 0.8394, it can be concluded that 87.95% or 83.94% (if the number of samples is taken into account) can be explained using Equation (5). Next, an ANOVA test performed on regression shows $F = 21.907$, which corresponds with $p = 0.00174$. It can be concluded that the multiple regression Equation (5) has significant explanatory power. Further, if the t-test is performed on coefficients of Equation (5), the following values are obtained; for the variable ID, $T = -2.7707$ which corresponds with $p = 0.0323$, and for the variable L_m, $T = 3.1878$, which corresponds with $p = 0.01888$. From the obtained values, it can be seen that both variables have a significant p-value, which supports the previous conclusion about the explanatory power of Equation (5).

From the performed analysis, it can be concluded that the printing time of the 3D-printer depends on both variables, i.e., ID and L_m.

Measurements of relative dielectric constant vs printing properties

Measurement results - PLA

Infill geometry	Infill density (%)	Printing time (min)	Mass of used material (g)	Length of material used (m)	Measurement no., capacity in (pF) 1	2	3	4	Average	Sample thickness (mm)	Calculated value of ε_r
square	33	24	7	0.89	6.30	6.20	6.20	6.20	6.23	5.87	2.1024
	66	31	11	1.35	7.30	7.30	7.30	7.40	7.33	5.81	2.4486
	100	39	14	1.83	8.40	8.40	8.30	8.40	8.38	5.84	2.8141
triangle	33	25	7	0.90	6	6.1	6	6	6.03	5.92	2.0522
	66	32	11	1.36	6.3	6.3	6.3	6.3	6.3	5.87	2.1277
	100	39	14	1.83	8.4	8.4	8.3	8.4	8.38	5.84	2.8141
corrugated	33	25	7	0.89	5.3	5.3	5.3	5.3	5.3	5.83	1.7778
	66	43	10	1.32	7.7	7.8	7.7	7.8	7.75	5.77	2.5729
	100	39	14	1.83	8.4	8.4	8.3	8.4	8.38	5.84	2.8141

Measurements of relative dielectric constant vs printing properties

Measurement results –ABS

Infill geometry	Infill density (%)	Printing time (min)	Mass of used material (g)	Length of material used (m)	Measurement no., capacity in (pF) 1	2	3	4	Average	Sample thickness (mm)	Calculated value of ε_r
square	33	28	6	0.92	6.6	6.5	6.6	6.6	6.58	5.81	2.1979
	66	39	10	1.4	7.8	7.9	7.9	7.8	7.85	5.79	2.6151
	100	51	13	1.89	8.9	9	8.9	8.9	8.93	5.84	2.9989
triangle	33	29	6	0.93	6.9	7	7	6.9	6.95	5.88	2.3513
	66	39	10	1.4	8	7.9	7.9	7.9	7.93	5.77	2.6310
	100	51	13	1.89	8.9	9	8.9	8.9	8.93	5.84	2.9989
corrugated	33	29	7	0.93	7	6.9	6.9	7	6.95	5.83	2.3313
	66	43	10	1.33	7.9	7.9	7.9	7.9	7.9	5.71	2.5954
	100	51	13	1.89	8.9	9	8.9	8.9	8.93	5.84	2.9989

Measurements of relative dielectric constant vs printing properties

- From this paper (previous tables): Kuzmanić, I., Vujović, I., Petković, M. *et al.* Influence of 3D printing properties on relative dielectric constant in PLA and ABS materials. *Prog Addit Manuf* **8**, 703–710 (2023). https://doi.org/10.1007/s40964-023-00411-0

  we can extract:
- Hence: relative dielectric constant CHANGES due to printing properties!
- References e.g. from next slide show material degradation due to various reasons possible at sea.

Some references for degradation of filament properties

- Zhang, S.-U. Degradation Classification of 3D Printing Thermoplastics Using Fourier Transform Infrared Spectroscopy and Artificial Neural Networks. Appl. Sci. 2018, 8, 1224. https://doi.org/10.3390/app8081224.
- Upadhyay, R.K.; Mishra, A.K.; Kumar, A. Mechanical Degradation of 3D Printed PLA in Simulated Marine Environment. Surf. Interfaces 2020, 21, 100778.
- Chen H, Shi Q, Shui H, Wang P, Chen Q and Li Z (2021) Degradation of 3D-Printed Porous Polylactic Acid Scaffolds Under Mechanical Stimulus. Front. Bioeng. Biotechnol. 9:691834. doi: 10.3389/fbioe.2021.691834
- Kaspar V, Rozlivka J. Chemical degradation of 3D printed products. Manufacturing Technology. 2020;20(1):45-48. doi: 10.21062/mft.2020.010

Some references for degradation of filament properties

- Orellana-Barrasa, J.; Ferrández-Montero, A.; Ferrari, B.; Pastor, J.Y. Natural Ageing of PLA Filaments, Can It Be Frozen? Polymers, 2022, 14, 3361. https://doi.org/10.3390/polym14163361
- Kam M, İpekçi A, Şengül Ö (2023) Investigation of the effect of FDM process parameters on mechanical properties of 3D printed PA12 samples using Taguchi method. J Thermoplast Compos Mater 36:307-325. doi: https://doi.org/10.1177/08927057211006459
- Adedotun D. Banjo, Vinamra Agrawal, Maria L. Auad, Asha-Dee N. Celestine, Moisture-induced changes in the mechanical behavior of 3D printed polymers, Composites Part C: Open Access, Volume 7, March 2022, 100243
- J. Crespo-Miguel, D. Garcia-Gonzalez, G. Robles, M. Hossain, J.M. Martinez-Tarifa, A. Arias, Thermo-electro-mechanical aging and degradation of conductive 3D printed PLA/CB composite, Composite Structures, Volume 316, 15 July 2023, 116992, https://doi.org/10.1016/j.compstruct.2023.116992

Flaws

- Printing time
- Operating conditions of printers
- Degradation
- Influence of environmental condition
- Many 3D printed parts must undergo an additional step such as machining or drilling, before use.
- 3D printed materials must be standardized and uniform.
- General material standards do not yet exist, companies must set and meet quality standards for their spare parts and more importantly, for materials and printing processes.

Conclusions

- The high standards of waste disposal regulations on ships also contribute to 3D printing technology with environmentally friendly PLA materials. With its properties of durability and strength, as well as ease of use, PETG material would also find its place in the production of spare parts on board.
- If we wish to use it in real conditions, the speed of 3D printers and their related software needs to increase.
- Various parts could be patented or protected by property laws.
- Materials should be resistant to environmental conditions and degradation as far as possible but without considerable influence on price.
- HENCE, we need faster 3D printers and more resistant materials to various influences.