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Polymers Selection for Harsh Environments to Be Processed Using Additive Manufacturing Techniques

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ABSTRACT In this paper, a methodology for selecting a combination of polymers and their associated additive manufacturing (AM) routes is presented. The binomial consisting of materials performance for the intended application and the most suitable AM process and its production strategy is solved by the application of a multicriteria approach along with a stringency level methodology. The case study has been the analysis of physical and radiation tolerance features of thermoplastic nature candidates for the additive manufacture of mechanical, electromechanical, and electrical components for harsh environments in a nuclear power plant. The obtained results allow select an AM route along with a production strategy based on large batches or small batches. Using a selective laser sintering additive manufacturing route, PP + EPDM can be a good option to manufacture mechanical heavily stressed components, whereas PA can be a versatile material to manufacture friction components or films and sheets for electrical applications. In addition, PE would be a good option for high voltage insulation. Finally, PS would be used in radio frequency and microwave applications. On the other hand, fused deposition modeling techniques are more suitable for several materials, such as PC for mechanical applications, PE for electromechanical applications, and IR for electrical/electronic applications.

INDEX TERMS Additive manufacturing, harsh environment, material selection, multicriteria analysis, thermoplastics.

I. INTRODUCTION

Reliability evaluation plays an important role in the design and development of any engineering system [1]. In a nuclear power plant, the radiation, temperature and moisture parameters are very relevant to ensure the polymer-based materials performance. Meanwhile, the reactor pressure vessel is designed, manufactured and operated in such a manner that it must not fail in service [2], other components of a nuclear power plant should be replaced periodically. Thus, the need for continuous online monitoring is becoming crucial considering the need for reactor license extension, the development of small and medium reactors (SMRs), and next-generation nuclear power plants [3].

In the past 20 years or so, there have been steady improvements in polymer purity and manufacturing [4]. In addition, conductive polymer composites have been receiving increased interest both from the scientific community and industry with a special focus on electromagnetic interference (EMI) shielding applications [5]. In fact, polymers are often used in electro-mechanical components of nuclear power plants that meet the R.G. 1.180 [6] requirements for electromagnetic emission and immunity of equipment.

Material selection studies are usually performed in the preliminary design stage [7]. There are a lot of characteristics that have to be necessarily considered when a polymer candidate is evaluated for an application at harsh environment in a nuclear plant. Some of these features are related to radiation tolerance and its influence on mechanical and electrical properties since radiation causes molecular-chain scission, which results in weakening and embrittlement of the polymer bond [8]. Some others are electrical properties such as volumetric resistivity or dielectric strength because they are essential for the evaluation of electrical insulation performance of dielectric polymers [9].

Another important group of properties to consider is the mechanical characteristics set. Focusing on polymer materials for applications in nuclear plants, it could be highlighted some thermal properties such as the thermal conductivity, the coefficient of linear expansion and other mechanical such as the tensile strength and the maximum elongation. In fact, the mechanical properties are very relevant to ensure that in case of seismic event the material can withstand elevated tensile, flexion and vibration stresses.

The manufacture of equipment for nuclear power plants embodies several challenges, since the manufacturing domain has different features such as the requirements of reliability and safety during the product manufacturing process [10]. Nowadays, customers, as the nuclear plant's owners, are no longer the passive buyers of manufacturing processes. Instead, they have become designers, who wish to participate in the customization of their goods prior to purchase [11].

Additive manufacturing (AM) techniques are well suited to the nuclear industry's requirements for low volume production, wide variety and highly critical plant components [12]. Thus, obsolete parts are particularly well-suited for this new technology as they and their designs are virtually difficult to obtain due to a lack of design information such as component drawings or bill of materials [13]. AM can address this obstacle using reverse engineering tools to conceive a computer-aided design (CAD) model. In 2016, the US Department of Energy granted Westinghouse $8 million for multiple R&D projects focused on the advancement of new technologies, including a project working on qualifying powder bed fusion additive manufacturing processes for nuclear components [14].

Advanced manufacturing processes like additive manufacturing are rising much interest in the manufacturing programs of equipment in the nuclear industry. While additive manufacturing has been proved extremely useful to accelerate the design of complex parts, we are still far from being able to apply 3D manufactured parts to the fabrication of critical components where both functionality and reliability play a central role. A sampling performed among papers of recent research on AM showed that hardly 5% emphasize on reliability, failure or degradation of the AM parts [15]. This endorses that a challenge for the AM research and development is to standardize processes, relating manufacturing process with microstructure and in service-behavior [16].

The selection problem of material-AM process binomial can be addressed, not only performing trial-error testing, but also performing recommendable previous analysis of suitability. Thus, a suitability analysis carried out before the trial-error testing can minimize unnecessary efforts to find the most recommendable material-AM process binomial, considering firstly the final part application. In the nuclear field, it is essential to develop a technique of materials selection for additive manufacturing where the final application is an equipment in the nuclear reactor environment.

Many subcomponents of main safety-related equipment of a nuclear power plant are manufactured using polymers. Some examples are the piping or the valves of boron analyzer or printed boards used in the controller mechanism of the reactor. Thus, the aim of this work is the development of a methodology to collect and analyze thermoplastics requirements to be used in the additive manufacturing of components in equipment under harsh conditions.

II. METHODOLOGY AND BACKGROUND

Traditional materials used in customary processes (like thermoforming) for the nuclear industry can include ABS, thermoplastic polyesters, polypropylene, polystyrene, acrylics and polyvinyl chloride [8]. However, not all polymers are suitable to be used in additive manufacturing techniques.

Polymer powders for additive manufacturing must exhibit thermoplastic behavior so that they can be melted and re-melted to permit bonding of one layer to another. In addition, thermoplastic materials are well-suited for powder bed processing because of their relatively low melting temperatures, low thermal conductivities, and low tendency for balling [17].

The selection of an AM material is highly dependent on the AM process that will utilize the material [18]. Nevertheless, the most important factor to ensure firstly is the material suitability for the intended application, or in other words, the functional suitability. Therefore, in the case of a nuclear plant, the candidate material should meet the technological requirements of the applications, such as, mechanical and electrical behavior or radiation tolerance.

To address this problem, an analysis methodology is developed (Fig.1) through the stages A to D, performing: i) a materials preselection (stage A), ii) a data collection stage (B) to obtain physical (mechanical, thermal and electrical) and radiation tolerance properties, iii) an stringency level methodology (stage C) to get the more suitable alternatives and finally iv) a multicriteria decision-making methodology (MCDM) for analyzing the trinomial generated by material, AM technique to process and the range of application of the final product (stage D).

The methodology stages are explained and developed as follows.

A. PRE-SELECTION OF THERMOPLASTICS FOR THE INTENDED APPLICATION

Polymers can be found in different locations in a nuclear power plant, specifically (by importance order) these are [19]:

- Polymeric parts in components of mechanical and electromechanical systems.
- Seals in building structures.
- Electrical devices.

Thus, in stage (A) of the methodology, the preselection of thermoplastics is based on the suitability for the three categories of applications in a nuclear power plant (Table 1).

Once categories according to the applications have been defined, a pre-selection of typical thermoplastics has been carried out (Table 2) considering the applications

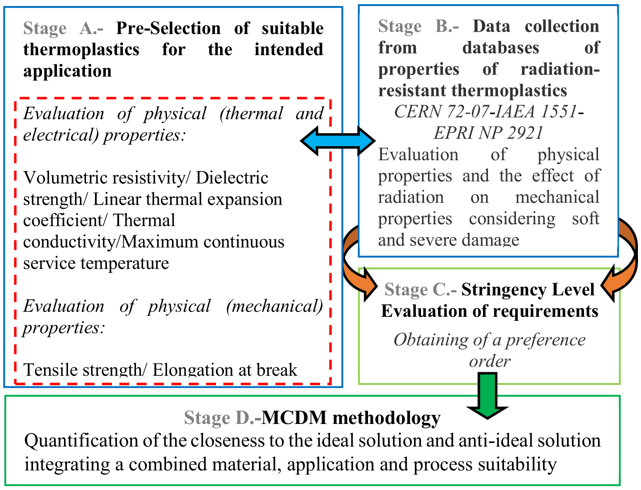


FIGURE 1. Methodology of analysis.

TABLE 1. Clasification categories and their applications.

Category		Equipment and type of applications
Mechanical	1	*Mechanical equipment*: heavily stressed components, cams, gears, couplings, racks, rollers.
	2	*Low friction applications*: bearings, guides, impellers, slides, valves, valve liners, wearing surface.
Electro-mechanical	3	*High voltage insulation*: magnet coils, high voltage switchers, transformers.
Electrical/ Electronical	4	*Radio frequency* and *microwave* applications.
	5	Films and sheets for *electrical applications.*

range related to the type of thermoplastic composition (viz: cellulosics, halogenated, polyolefines, styrene polymers and vinylesters) and the scientific and technical literature [8], [20]–[22].

B. DATA COLLECTION FROM DATABASES OF PROPERTIES OF RADIATION-RESISTANT THERMOPLASTICS

The data collection is carried out from different sources or databases such as IAEA 1551 [23], EPRI NP 2921 [24] and CERN 72-07 [25]. In addition, technical handbooks [8], [20] have been used in the collection process (Fig.2).

Previously to data collection and analysis, several technological requirements have been selected according to their ability to describe functionality and environment-related conditions (Table 3).

Tables 4 and 5 show the data related to mechanical thermal and electrical properties collected using the different sources and databases.

On the other hand, Table 6 provides the thresholds in terms of gamma radiation for soft damage and severe damage (defined as a reduction of a 50% in the tensile strength and maximum elongation). These upper bounds have been selected performing data collection tasks using IAEA 1551, EPRI NP 2921 and CERN 72-07 [23]–[25] sources.

TABLE 2. Pre-selected polymers.

Classification by composition	Polymers preselected	Assigned code	Classification according to Table I
Cellulosics	Acetil resin (Delrin)	A	1
	Acrylic resin: Polymethylmethacrylate	B	1
	Cellulose acetate	C	1
	Cellulose acetate butyrate	D	1
	Cellulose nitrate	E	1
	Ethyl cellulose (film)	F	4
Halogenated	Plasticized polyvinylchloride (cable insulation)	G	4
	Polychlorotrifluoroethylene (PCTFE)	H	4
	Polyvinylidenechloride	I	4
	Teflon FEP	J	2, 4
	Polytetrafluoroethylene (PTFE)	K	1, 2
	Polyamide	L	2, 5
	Polycarbonate (film)	M	2, 3, 4
Polyolefines	Polyethylene (cable insulation)	N	3, 4
	Polypropylene	O	3, 4
	Polypropylene-ethylene polyallomer	P	1, 4
	Ionomer resin	Q	5
Styrene Polymers	Polysterene	R	4
Vinylesters	Polyvinylbutyral	S	4
	Polyvinylformal	T	1, 2
	Polyvinylcarbazole	U	1, 2

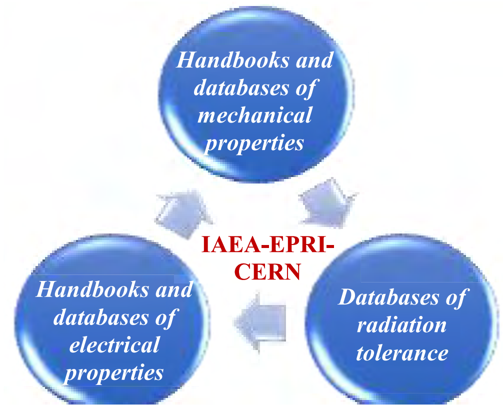


FIGURE 2. Scheme of data collection sources.

Whereas the values shown in Table 6 are intended to quantify the radiation tolerance of analyzed polymers, Table 7 shows typical values of gamma radiation found in the reactor environment. These values are used as critical thresholds to evaluate the radiation-tolerance characteristics of the different polymers analyzed.

Therefore, the radiation thresholds for the accumulated doses of normal operating condition for the licensed lifetime of the plant (RR_{normal}) and for the LOCA accident (RR_{acc}) are defined in two areas, main pumps system with medium

TABLE 3. Selected materials requirements to be analyzed according to their in-service functionality and environment conditions.

Requirements /in-service behavior	Functionality conditions				Environment-related conditions	
	Mechanical resistance	**Ductility**	**Thermal expansion and conductivity**	**Electrical properties**	**Temperature resistance**	**Irradiation resistance**
TS	x					
EL		x				
α			x			
K			x			
T_{max}					x	
ρ				x		
DS				x		
$IRSD$						x
$IRSED$						x

Notes in Table III: Tensile strength-TS; Elongation-EL; Lineal thermal expansion coefficient-α; Thermal conductivity-K, Maximum continuous service temperature-T_{max}; Volumetric resistivity-ρ; Dielectric strength-DS; Irradiation resistance for soft damage-$IRSD$; Irradiation resistance for severe damage-$IRSED$.

TABLE 4. Mechanical and thermal properties of analyzed materials [20]–[22].

Code	Tensile strength (TS) [MPa]	Elongation (EL) [%]	Lineal thermal expansion coefficient (α) [m/ºC]
A	68.16	30.0	$2.29\cdot10^{-6}$
B	73.55	4.5	$2.29\cdot10^{-6}$
C	36.40	20.0	$4.57\cdot10^{-6}$
D	28.80	60.0	$4.32\cdot10^{-6}$
E	52.20	30.0	$3.05\cdot10^{-6}$
F	41.20	40.0	$5.08\cdot10^{-6}$
G	21.60	310.0	$1.98\cdot10^{-6}$
H	33.60	50.0	$1.78\cdot10^{-6}$
I	25.40	200.0	$4.83\cdot10^{-6}$
J	20.60	265.0	$3.56\cdot10^{-6}$
K	23.34	250.0	$3.05\cdot10^{-6}$
L	52.17	62.0	$2.11\cdot10^{-6}$
M	42.56	96.0	$1.73\cdot10^{-6}$
N	18.73	655.0	$2.79\cdot10^{-6}$
O	31.97	700.0	$2.54\cdot10^{-6}$
P	30.01	770.0	$4.06\cdot10^{-6}$
Q	15.30	408.0	$4.32\cdot10^{-6}$
R	172.60	50.0	$3.81\cdot10^{-6}$
S	30.20	1.0	$2.16\cdot10^{-6}$
T	15.10	225.0	$1.60\cdot10^{-5}$
U	50.80	2.0	$6.50\cdot10^{-6}$

radiation doses (MRD), and steam generator with high radiation doses (HRD):

- Main pumps room

$$RT_{normal}(MRD) = 3 \cdot 10^5 \text{ Rads} \tag{1}$$

$$RT_{acc}(MRD) = 8 \cdot 10^4 \text{ Rads} \tag{2}$$

TABLE 5. Electrical properties, thermal conductivity and maximum working temperature [20]–[25].

Code	Volumetric resistivity (ρ) [Ω·m]	Dielectric strength (DS) [V/m]	Thermal conductivity (K) [W/m·ºC]	Maximum continuous service temperature (T_{max})[ºC]
A	$1\cdot10^{12}$	$2.17\cdot10^{5}$	0.25	82.22
B	$1\cdot10^{12}$	$2.36\cdot10^{5}$	0.25	82.22
C	$1\cdot10^{11}$	$1.87\cdot10^{5}$	0.33	90.56
D	$1\cdot10^{13}$	$2.36\cdot10^{5}$	0.09	94.44
E	$1\cdot10^{14}$	$1.97\cdot10^{5}$	0.23	71.11
F	$1\cdot10^{11}$	$3.94\cdot10^{5}$	0.29	87.78
G	$1\cdot10^{13}$	$2.36\cdot10^{5}$	0.14	119.44
H	$1\cdot10^{14}$	$2.36\cdot10^{5}$	0.22	204.44
I	$1\cdot10^{14}$	$1.89\cdot10^{5}$	0.13	187.78
J	$1\cdot10^{16}$	$1.77\cdot10^{6}$	0.25	204.44
K	$1\cdot10^{16}$	$3.07\cdot10^{5}$	0.25	121.11
L	$1\cdot10^{11}$	$1.57\cdot10^{5}$	0.24	121.11
M	$1\cdot10^{14}$	$1.89\cdot10^{5}$	0.20	141.67
N	$1\cdot10^{14}$	$3.15\cdot10^{5}$	0.50	91.11
O	$1\cdot10^{14}$	$3.15\cdot10^{5}$	0.12	121.11
P	$1\cdot10^{14}$	$1.77\cdot10^{5}$	0.22	60.00
Q	$1\cdot10^{14}$	$1.57\cdot10^{5}$	0.28	51.67
R	$1\cdot10^{16}$	$2.76\cdot10^{5}$	0.33	65.00
S	$1\cdot10^{14}$	$1.38\cdot10^{5}$	0.13	82.22
T	$1\cdot10^{14}$	$1.42\cdot10^{5}$	0.17	40.00
U	$1\cdot10^{14}$	$1.77\cdot10^{5}$	0.17	60.00

TABLE 6. Irradiation resistance until experience soft and severe damage [23]–[25].

	Irradiation resistance for soft damage			Irradiation resistance for severe damage (CERN 72-07)	
	IAEA 1551, gamma (Rads)	EPRI NP 2921, gamma (Rads)	CERN 72-07, gamma (Rads)	Value for the TS decreased to 50% (Rads)	Value for the E% decreased to 50% (Rads)
A	-	$6.0\cdot10^{5}$	$2\cdot10^{5}$	$5\cdot10^{6}$	$2\cdot10^{6}$
B	$8\cdot10^{5}$	-	$7\cdot10^{5}$	$3\cdot10^{7}$	$3\cdot10^{7}$
C	$3\cdot10^{6}$	$8.0\cdot10^{5}$	$7\cdot10^{5}$	$8\cdot10^{7}$	$4\cdot10^{7}$
D	-	$3.4\cdot10^{5}$	$8\cdot10^{5}$	$5\cdot10^{7}$	$5\cdot10^{7}$
E	-	$5.0\cdot10^{5}$	$7\cdot10^{5}$	$6\cdot10^{7}$	$1\cdot10^{7}$
F	-	$1.5\cdot10^{6}$	$1\cdot10^{6}$	$3\cdot10^{7}$	$8\cdot10^{6}$
G	$1\cdot10^{7}$	$1.2\cdot10^{6}$	$2\cdot10^{7}$	$2\cdot10^{8}$	$8\cdot10^{7}$
H	$1\cdot10^{6}$	$1.2\cdot10^{6}$	-	$1\cdot10^{8}$	$6\cdot10^{7}$
I	$4\cdot10^{6}$	$3.7\cdot10^{6}$	$3\cdot10^{6}$	$9\cdot10^{8}$	$3\cdot10^{8}$
J	$1\cdot10^{4}$	$5.0\cdot10^{5}$	$1\cdot10^{6}$	$7\cdot10^{5}$	$3\cdot10^{5}$
K	-	$1.5\cdot10^{4}$	$4\cdot10^{4}$	$1\cdot10^{6}$	$1\cdot10^{5}$
L	$7\cdot10^{5}$	$7.0\cdot10^{6}$	$5\cdot10^{5}$	$7\cdot10^{7}$	$7\cdot10^{7}$
M	$4\cdot10^{6}$	$7.0\cdot10^{5}$	$4\cdot10^{6}$	$3\cdot10^{8}$	$9\cdot10^{7}$
N	$1\cdot10^{7}$	$3.8\cdot10^{5}$	$1\cdot10^{7}$	$2\cdot10^{8}$	$7\cdot10^{7}$
O	-	$3.0\cdot10^{5}$	$3\cdot10^{6}$	$1\cdot10^{7}$	$5\cdot10^{6}$
P	$2\cdot10^{6}$	$1.0\cdot10^{6}$	$2\cdot10^{6}$	$5\cdot10^{7}$	$8\cdot10^{6}$
Q	-	$2.0\cdot10^{6}$	$3\cdot10^{7}$	$1\cdot10^{9}$	$9\cdot10^{7}$
R	-	$4.4\cdot10^{6}$	$5\cdot10^{6}$	$7\cdot10^{8}$	$3\cdot10^{8}$
S	$8\cdot10^{8}$	$2.0\cdot10^{7}$	$9\cdot10^{8}$	$3\cdot10^{8}$	$3\cdot10^{8}$
T	$4\cdot10^{6}$	$3.0\cdot10^{6}$	$5\cdot10^{6}$	$8\cdot10^{7}$	$4\cdot10^{8}$
U	$1\cdot10^{7}$	$1.6\cdot10^{7}$	$1\cdot10^{7}$	$1\cdot10^{9}$	$3\cdot10^{9}$

- RPV nozzles room

$$RT_{normal}(HRD) = 7 \cdot 10^8 \text{ Rads} \tag{3}$$

$$RT_{acc}(HRD) = 9 \cdot 10^6 \text{ Rads} \tag{4}$$

TABLE 7. Reactor building operating conditions under normal and accident scenario.

Operating condition	Temperature (ºC)		Moisture (%)		Radiation gamma (Rads)*
	Min	Max	Min	Max	
Normal	10	50	10	65	$3\cdot10^5$(main pumps) $7\cdot10^8$ (steam generator)
Accident	45	145	-	100	$8\cdot10^4$ (main pumps) $9\cdot10^6$ (steam generator)

Note *: for normal operating case, the indicated radiation is the accumulated level for 40 years of licensed lifetime; for accident, the indicated radiation is produced in the first instants of loss of coolant accident (LOCA).

C. STRINGENCY LEVEL EVALUATION

Stringency level methodology (SLM) is a suitable tool for selecting materials for high demanding applications. In this work, this methodology is used to analyze physical and mechanical properties and radiation-tolerance characteristics of the polymers preselected in the stage A of the methodology. This methodology assigns several stringency levels for each technical feature requirement of materials [26]–[28]. Fig.3 provides the stringency level (SL) calculation as a function of the ratio between requirements analyzed (i.e. the ratio between the described requirement (L_s) and the maximum value of this requirement in the distribution of all analyzed materials $L_{s(max)}$).

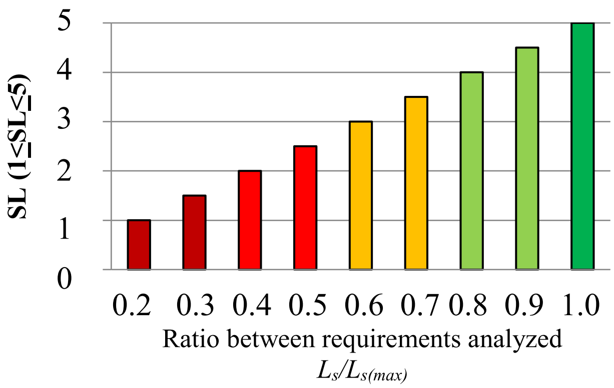


FIGURE 3. Stringency level assignation according to the ratio between requirements analyzed.

The procedure of stringency level calculation is shown as follows for each requirement analyzed (viz: α, TS,EL, K, T_{max}, ρ and DS).

1) THERMAL EXPANSION COEFFICIENT (α)

It is required that the polymer does not exhibit a big value of thermal expansion coefficient to reduce dimensional variabilities depending on the temperature. The Eq.5 allows the calculation of Stringency Level (SL) for this requirement:

$$SL = 5.00 \text{ for } min\{L_s \text{ (all specifications)}\} \tag{5}$$

The stringency levels of the remaining standard requirements are calculated as follows:

$$SL = \frac{L_{s(\min)}}{L_s} SL_{(\max)} \tag{6}$$

2) OTHER MECHANICAL AND THERMAL PROPERTIES (TS, EL, K, T_{max}, ρ AND DS)

For isolation and electromagnetic interference (EMI) shielding applications according to the requirements described by R.G. 1.180 [6], high volumetric resistivity and dielectric strength are suitable. In addition, high thermal conductivity and temperature resistance are recommendable to ensure thermal stability. Finally, tensile properties such as tensile strength (TS) and maximum elongation (E) are usually measured to check if damage by radiation has occurred when values are lower than expected. Therefore, these physical properties should exhibit a high value to ensure the materials performance. It assigns the maximum level of stringency to the maximum value of the distribution, according to the following equation:

$$SL = 5.00 \text{ for } max\{L_s(\text{all specifications})\} \tag{7}$$

The stringency levels for the rest of standard requirements are calculated as follows:

$$SL = \frac{L_s}{L_{s\,(\max)}} SL_{(\max)} \tag{8}$$

Once calculated the SL for each requirement of each material, the overall SL for each material (SL_j) is obtained according to Eq.9:

$$\begin{aligned} SL_j &= a \cdot [SL\,(TS) + SL\,(EL)] \\ &\quad + b \cdot [SL\,(\alpha) + SL\,(K) + SL\,(Tmax)] \\ &\quad + c \cdot [SL\,(\rho) + SL\,(DS)] \end{aligned} \tag{9}$$

Table 8 exhibits the values of coefficients depending if the material is intended for a mechanical or electrical application, or both types of applications. The coefficients weight the contribution of each set of technological requirements, providing more relevance at the subset of the specific properties for the application typology.

TABLE 8. Coefficients (relative weights) for the stringency level (SL_j) calculation.

Coefficient	Mechanical component (Categories 1 and 2)	Electrical component (Categories 3, 4 and 5)	Electro-mechanical component*
a	3/8	1/4	1/3
b	3/8	3/8	1/3
c	1/4	3/8	1/3

Note (*): Combination of a mechanical category -1 and 2- with electrical category -3,4 and 5-).

Using Eqs. 1 to 9 and the coefficients provided in Table 8, stringency levels of each physical characteristic and the global $SLj$for each material are calculated (Table 9).

TABLE 9. Stringency level (SL_j) associated to the physical (mechanical, thermal and electrical) properties of analyzed polymers.

Code	Type *	SL (TS)	SL (EL)	SL (α)	SL (K)	SL (T_{max})	SL (ρ)	SL (DS)	SLj
A	1	1.97	0.19	3.78	2.33	2.01	0.00	0.61	3.86
B	1	2.13	0.03	3.78	2.33	2.01	0.00	0.61	3.86
C	1	1.05	0.13	1.89	3.10	2.21	0.00	0.67	3.14
D	1	0.84	0.39	2.00	0.85	2.31	0.00	0.53	2.40
E	1	1.51	0.19	2.84	2.13	1.74	0.10	0.67	3.18
F	4	1.19	0.26	1.70	2.71	2.15	0.00	0.56	2.82
G	4	0.63	2.01	4.37	1.28	2.92	0.01	1.11	3.88
H	4	0.97	0.32	4.87	2.05	5.00	0.05	0.67	4.81
I	4	0.74	1.30	1.79	1.16	4.59	0.05	0.67	3.36
J	2, 4	0.60	1.72	2.43	2.33	5.00	5.00	0.53	5.69
K	1, 2	0.68	1.62	2.84	2.33	2.96	5.00	5.00	5.16
L	2, 5	1.51	0.40	4.10	2.25	2.96	0.00	0.87	3.74
M	2, 3, 4	1.23	0.62	5.00	1.82	3.46	0.05	0.44	4.06
N	3, 4	0.54	4.25	3.10	4.65	2.23	0.05	0.53	4.96
O	3, 4	0.93	4.55	3.41	1.09	2.96	0.05	0.89	4.19
P	1, 4	0.87	5.00	2.13	2.04	1.47	0.05	0.89	3.85
Q	5	0.44	2.65	2.00	2.56	1.26	0.05	0.50	2.97
R	4	5.00	0.32	2.27	3.06	1.59	5.00	0.44	5.80
S	4	0.88	0.01	4.01	1.16	2.01	0.05	0.78	2.93
T	1, 2	0.44	1.46	0.54	1.57	0.73	0.05	0.39	1.79
U	1, 2	1.47	0.01	1.33	1.57	1.22	0.05	0.40	2.11

Note (*): Category 1. Mechanical: heavily stressed components. Cams, gears, couplings, racks, rollers; **Category 2.** Low friction applications: bearings, guides, impellers, slides, valves, valve liners, wearing surface; **Category 3.** High voltage insulation: magnet coils, high voltage switchers, transformers; **Category 4.** Radiofrequency applications; **Category 5.** Films and sheets for electrical applications;

Thus, Table 10 shows preference order obtained from the stringency level evaluation of physical (mechanical, thermal and electrical) properties of analyzed polymers.

TABLE 10. Preference order according to the stringency evaluation of physical/mechanical properties.

Category	Materials selection order (by code)
1	K>A=B>P
2	J>K>M>L
3	N>O>M
4	R>J>N>H>O>G>E
5	L>Q

3) RADIATION RESISTANCE EVALUATION

The calculation to evaluate the radiation resistance is developed according to the Eqs 10 to 14 using radiation thresholds (RR_{normal} and RR_{acc}) and the radiation levels (RR_i) that cause pernicious effects (soft-medium damage) on mechanical properties of the polymers considered in this work:

$$SL = 1.00 \quad (RR_j < RT_{acc-MRD}) \tag{10}$$

$$SL = 2.00 \quad (RT_{acc-MRD} \leq RR_j < 1.75\, RT_{acc-MRD}) \tag{11}$$

$$SL = 3.00 \quad (1.75\, RT_{acc-MRD} \leq RR_j < 2.75\, RT_{acc-MRD}) \tag{12}$$

$$SL = 4.00 \quad (2.75\, RT_{acc-MRD} \leq RR_j < RT_{normal-MRD}) \tag{13}$$

$$SL = 5.00 \quad (RR_j \geq RT_{normal-MRD}) \tag{14}$$

Analogously, the evaluation for severe damage using the thresholds indicated in Table 1 is performed using Eqs. 15 to 19:

$$SL = 1.00 \quad (RR_j < RT_{acc-HRD}) \tag{15}$$

$$SL = 2.00 \quad (RT_{acc-HRD} \leq RR_j < 1.75\, RT_{acc-HRD}) \tag{16}$$

$$SL = 3.00 \quad (1.75\, RT_{acc-HRD} \leq RR_j < 2.75\, RT_{acc-HRD}) \tag{17}$$

$$SL = 4.00 \quad (2.75\, RT_{acc-HRD} \leq RR_j < RT_{normal-HRD}) \tag{18}$$

$$SL = 5.00 \quad (RR_j \geq RT_{norma-HRD}) \tag{19}$$

The calculation using Eqs. 10 to 19 is performed for both medium radiation doses (MRD), and high radiation doses (HRD) as Eqs. 1 to 4 exhibit. Table 11 presents the stringency levels for each polymer according to the evaluation considering minimum-medium and severe damage.

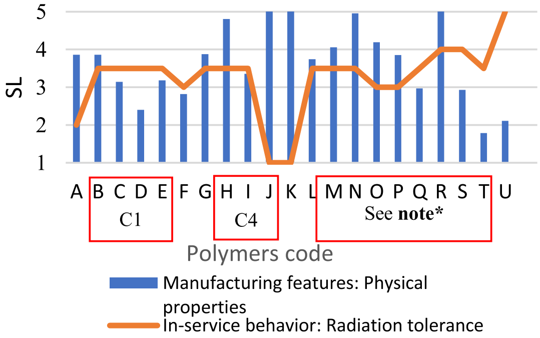
TABLE 11. Stringency levels (SL'_{ij}) associated to radiation resistance of analyzed polymers.

	Min (IAEA 1551/EPRI 2921, /CERN 72-07)	*SL'* (minimum -medium damage)	Min (50%TS, 50%E%)	*SL'* (severe damage)	*SL'* Mean (radiation tolerance)
A	$2.0 \cdot 10^5$	3	$2 \cdot 10^6$	1	2.0
B	$7.0 \cdot 10^5$	5	$3 \cdot 10^7$	2	3.5
C	$7.0 \cdot 10^5$	5	$4 \cdot 10^7$	2	3.5
D	$3.4 \cdot 10^5$	5	$5 \cdot 10^7$	2	3.5
E	$5.0 \cdot 10^5$	5	$1 \cdot 10^7$	2	3.5
F	$1.0 \cdot 10^6$	5	$8 \cdot 10^6$	1	3.0
G	$1.2 \cdot 10^6$	5	$8 \cdot 10^7$	2	3.5
H	$1.0 \cdot 10^6$	5	$6 \cdot 10^7$	2	3.5
I	$3.0 \cdot 10^6$	5	$3 \cdot 10^8$	3	3.5
J	$1.0 \cdot 10^4$	1	$3 \cdot 10^5$	1	1.0
K	$1.5 \cdot 10^4$	1	$1 \cdot 10^5$	1	1.0
L	$5.0 \cdot 10^5$	5	$7 \cdot 10^7$	2	3.5
M	$7.0 \cdot 10^5$	5	$9 \cdot 10^7$	2	3.5
N	$3.8 \cdot 10^5$	5	$7 \cdot 10^7$	2	3.5
O	$3.0 \cdot 10^5$	5	$5 \cdot 10^6$	1	3.0
P	$1.0 \cdot 10^6$	5	$8 \cdot 10^6$	1	3.0
Q	$2.0 \cdot 10^6$	5	$9 \cdot 10^7$	2	3.5
R	$4.4 \cdot 10^6$	5	$3 \cdot 10^8$	3	4.0
S	$2.0 \cdot 10^7$	5	$3 \cdot 10^8$	3	4.0
T	$3.0 \cdot 10^6$	5	$4 \cdot 10^8$	2	3.5
U	$1.0 \cdot 10^7$	5	$3 \cdot 10^9$	5	5.0

Using the results provided by Tables 9 and 11, Fig.4 shows the calculatedSL_j (physical features crucial for the manufacturing performance) *and* SL'_j (radiation tolerance crucial for the in-service behavior).

Therefore, Fig.5 provides a preferential order for selection considering the most relevant materials features (mean of physical and mechanical properties and radiation tolerance) that impact in their suitability for the intended application.

Switching to the selection of AM route to process the materials selected according to their industrial performance some studies have been reviewed (Table 12). Thus Pattinson & Hart [22] demonstrated good results performing AM of pure cellulosic objects via extrusion of cellulose polymers. Another study carried out by Salmoria *et al.* [29] demonstrated good behavior in Polymethylmethcrylate and Polysterene additively manufactured by selective laser sintering (SLS). Haigh *et al.* [30] have used a technique termed melt electrospinning to manufacture with



Note (*): L-Categories 2 and 5; M-Categories 2, 3 and 4; N and O-Categories 3 and 4; P-Categories 1 and 4; Q-Category 5; R and S-Category 4; T and U-Categories 1 and 2.

FIGURE 4. Stringency level calculation for physical (mechanical, thermal and electrical) properties and in-service behavior regarding radiation.

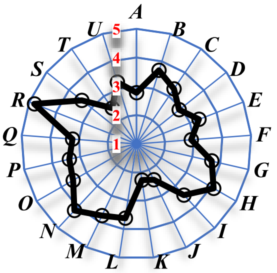


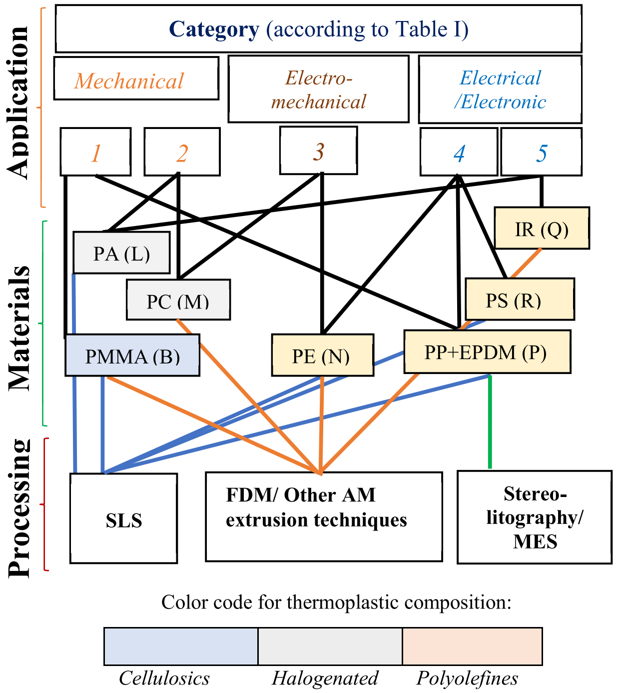
FIGURE 5. Preference order based on the SL methodology.

TABLE 12. Additive manufacturing according to the typology of the selected polymers [22], [29]–[34].

Typology(s) or compositional type(s)	AM process
Cellulose polymers	Extrusion of cellulose polymers [22]
Polymethylmethcrylate and Polysterene	Selective lase sintering (SLS) [29]
Polypropylene	Melt electrospinning with polypropylene microfibers [30].
Polyamide	Selective lase sintering (SLS) [31].
Polycarbonate	Fused deposition modeling (FDM) process with polycarbonate powder [32]
Polyethylene, polypropylene, polyamide	Implementation of Polyethylene, polypropylene, polyamide in laser sintering routes [33].
Ionomer polymers	Fused filament additive process to manufacture with ionomer polymers [34].

polypropylene microfibers. Bai et al. [31] have used SLS technique to additively manufacture with polyamide. Wong and Hernandez [32] mentioned the suitability of polycarbonate powder in fused deposition modeling (FDM) process. Wegner [33] studied the implementation of Polyethylene, polypropylene, polyamide in laser sintering routes. Carrico *et al.* [34] used a new fused filament additive process to manufacture with ionomer polymers.

If the best two options are selected for each category, we obtain the following potential materials for their related additive manufacturing route (Fig.6).



Abbreviation- PC-Polycarbonate (M); PE-Polyethylene (N); PA-Polyamide (L); PP+EPDM- Polypropylene ethylene polyallomer (P); PMMA- Polymethylmethacrylate (B); PS- Polysterene (R); IR-Ionomer resin (Q). SLS-Selective laser sintering; FDM- Fused deposition modeling; MES-Melt electrospinning.

FIGURE 6. Relationship flowchart: materials, applications and AM routes.

Whereas, the advanced melt electrospinning (MES) technique could be applied clearly to Polypropylene ethylene polyallomer (P), Table 13 shows the candidate materials for FDM and SLS processes.

TABLE 13. Candidate materials for FDM and SLS processes.

Category	FDM materials	SLS materials
1	Polymethylmethcrylate (B)	PP+EPDM (P)/ Polymethylmethcrylate (B)
2	Polycarbonate (M)	Polyamide (L)
3	Polycarbonate (M) and Polyethylene (N)	Polyethylene (N)
4	Polyethylene (N)	Polyethylene (N), Polypropylene ethylene polyallomer (P) Polyethylene terephthalate (R),
5	Ionomer resin (Q)	Polyamide (L)

In addition to FDM and SLS techniques, advanced melt electrospinning (MES) is also well suited for the case of Polypropylene ethylene polyallomer (P). Once obtained the most suitable options according to the materials in-service behavior, the problem to solve consists of selecting the best combination of material and type of process (in this case, FDM and SLS are specifically analyze due to their availability in the industry) for every category of application (1 to 5). FDM is often used to build complex geometries and functional parts, including prototypes and low-volume production pieces. On the other hand, SLS is useful to build versatile parts with high elongation at break. In addition, SLS production parts and prototypes provide lightweight, heat and chemical resistant solutions when the selected polymers are the suitable. In 2016, SLS was the most used technology (38%) followed by FDM and stereolitography, SLA [35]. This problem is addressed in the following stage of the methodology using multicriteria decision making concepts.

D. MULTICRITERIA REQUIREMENTS ASSESSMENT

In the selection of a manufacturing route, it must be understood that materials selection according to its in-service behavior and choice of process are interdependent and, therefore, any change to one aspect will inevitably lead to changes in the others. The principal factors, which determine the final choice of a manufacturing route, are the component geometry, size, the required mechanical performance and the envisaged scale of production [36]. The AM categories, as defined by *ASTM F42* and *ISO TC 261* committees, used currently in the manufacture of nuclear components [12] are the materials extrusion (like FDM) and powder bead fusion (like SLS).

The perfect combination of material and AM route (closest to the ideal-solution) should be determined by the selection of the process that it is more adjusted to the required production characteristics such as batch small or geometry complexity, among others. Besides, the manufacturing cost and the prices of the polymers should be considered. To this end, manufacturing and materials costs have been collected (Tables 14 and 15).

TABLE 14. Manufacturing costs per part based on [37], [38].

Requirements/in-service behavior	FDM	Laser sintering
Production rate per hour (units/h)	1.11	17.66
Machine cost per part ($)	2.11	0.42
Labor cost per part ($)	0.06	0.03
Total cost per part (called MFC) including materials, machine, labor and other costs ($)	3.58	1.76

TABLE 15. Costs of selected materials [39], [40].

Polymers	Cost (called MTC) ($/kg)
PC-Polycarbonate (M)	1.14
PE-Polyethylene HD (N)	0.73
PA-Polyamide (L)	0.76
PP+EPDM- Polypropylene ethylene polyallomer (P)	0.61
PMMA- Polymethylmethcrylate (B)	0.84
PS- Polysterene (R)	0.76
IR-Ionomer resin (Q).	27.99

The following *j* constraints (Eq.20) are considered to calculate $<SL_j>$ global for the analysis of manufacturing process and materials performance.

$$Constraints = \begin{cases} \text{MFC} \rightarrow \text{min} \\ \text{PR} \rightarrow \text{max} \\ SLj \rightarrow \text{max} \\ SL'j, \rightarrow \text{max} \\ \text{MTC} \rightarrow \text{min} \end{cases} \tag{20}$$

Where: MFC is the manufacturing total cost per part, PR is the production rate per hour, SL_j is global stringency level related to physical properties for every analyzed material, SL'_j, is mean of the global stringency levels related to radiation tolerance for every analyzed material, considering soft damage and severe damage.

The preference order -obtained in the subsection c and provided in Tables 9 to 11 and Fig.4- was calculated considering every intended application. However, in this stage of analysis (stage D), the AM process and their constraints are integrated.

Therefore, there are different conflicts to be solved due to some combinations of materials and processes belong to several categories of application (i.e: PA(L)↔SLS belongs to 2 and 5, PC(M)↔FDM belongs to 2 and 3, PE(N)↔FDM and PE(N)↔SLS belong to 3 and 4 or PP+EPDM(M) belongs to 1 and 4). Thus, Fig.7 shows the material and associated AM processes grouped by category, using interrelationship diagrams.

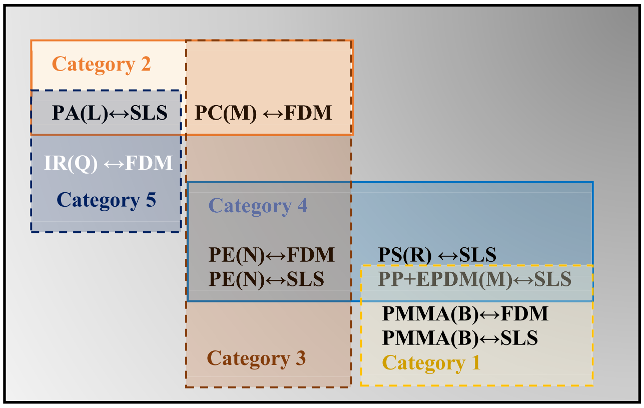


FIGURE 7. Interrelationship diagram: material and associated AM processes grouped by category.

Therefore, the ideal solution should be designed as the perfect balance between selected materials, AM route to process the material and the perfect fit of the material according to the categories of application (1 to 5 in Fig.6).

Table 16 exhibits the possibilities established in the interrelationship diagram (Fig. 6) and the stringency levels calculated (Eqs. 5 to 8) using the constraints shown in Eq.20.

According to the values shown in Table 16, the global stringency level including the impact of manufacturing and material cost and the suitability of materials for the intended

TABLE 16. **Potential options to implement and the stringency levels associated to the manufacturing-material binomial.**

Category	Material and AM technique	Manufacturing process		Material performance	
		SL (*MFC*)	SL (*PR*)	SL (*MTC*)	*SLj* global mean
1	PMMA (B) ↔ FDM	2.46	0.31	3.63	3.68
	PMMA (B) ↔ SLS	5.00	5.00	3.63	3.68
	PP+EPDM (P) ↔ SLS	5.00	5.00	5.00	3.43
2	PC (M) ↔ FDM	2.46	0.31	2.67	3.78
	PA (L) ↔ SLS	5.00	5.00	4.01	3.62
3	PC (M) ↔ FDM	2.46	0.31	2.67	3.78
	PE (N) ↔ FDM	2.46	0.31	4.18	4.23
	PE (N) ↔ SLS	5.00	5.00	4.18	4.23
4	PE (N) ↔ FDM	2.46	0.31	4.18	4.23
	PE (N) ↔ SLS	5.00	5.00	4.18	4.23
	PP+EPDM (P) ↔ SLS	5.00	5.00	5.00	3.43
	PS (R) ↔ SLS	5.00	5.00	4.01	4.9
5	PA(L) ↔ SLS	5.00	5.00	4.01	3.62
	IR(Q) ↔ FDM	2.46	0.31	0.11	3.24

TABLE 18. **Stringency level calculation for the material and AM route combination.**

Category		Material and AM technique	Small batches (SB)	Large batches (LB)
1	1a	PMMA (B) ↔ FDM	3.67	3.43
	1b	PMMA (B) ↔ SLS	3.67	5.24
	1c	PP+EPDM (P) ↔ SLS	3.82	5.66
2	2a	PC (M) ↔ FDM	3.50	3.11
	2b	PA (L) ↔ SLS	3.72	5.36
3	3a	PC (M) ↔ FDM	3.50	3.11
	3b	PE (N) ↔ FDM	4.22	3.85
	3c	PE (N) ↔ SLS	4.22	5.65
4	4a	PE (N) ↔ FDM	4.22	3.85
	4b	PE (N) ↔ SLS	4.22	5.65
	4c	PP+EPDM (P) ↔ SLS	3.82	5.66
	4d	PS (R) ↔ SLS	4.68	5.84
5	5a	PA(L) ↔ SLS	3.72	5.36
	5b	IR(Q) ↔ FDM	2.46	1.95

application is calculated using Eq.21.

$$SL_j(\mathrm{MF\&M}) = a \cdot [SL(MFC) + SL\ (PR)] + b \cdot [SL(MTC)] + c \cdot [\mathrm{SL}j\ global\ mean\ (\mathrm{material})] \qquad (21)$$

Table 17 exhibits the value of coefficients depending of the manufacturing strategy and necessity (small and large batches production).

TABLE 17. **Coefficients (relative weights) for the stringency level (SL_j) calculation.**

Coefficient	Small batches	Large batches
a	0	1/4
b	1/4	3/8
c	3/4	3/8

According to the use of these coefficients, Table 18 provides the global stringency level for the jointly study of material and manufacturing process for the case of small batches or ad-hoc manufacturing and for large batches.

In this stage, the normalization of criteria values is carried out using a normalization vector, grouping thus by category and considering therefore the dispersion among values. The normalized value r_{ij} is calculated by Eq.22:

$$< r_{ij} >= \frac{SL_j}{\sqrt{\sum_{i=1}^{M} SL_j^2}} \quad \text{if} \quad SL_J = \frac{1}{n}\sum_{1}^{n} SL_{ij} \qquad (22)$$

Where n is the number of materials selected in each category (1 to 5) according to Table 12, SL_j represents the stringency level of the j-material, r_j represents the value of the new normalized decision-making matrixes, considering in the study, the constraints (Eq.20) associated to the manufacturing process and materials selection.

The multicriteria evaluation of alternatives problem is usually defined by criterion matrix as follows, using the *SL*, calculated by the constraints indicated in Eq.20, to process the materials selected based on the stringency level methodology (shown in Table 9 and 11).

$$\begin{bmatrix} < \boldsymbol{r_{11}} > & < \boldsymbol{r_{12}} > & \cdots & < \boldsymbol{r_{1k}} > \\ < \boldsymbol{r_{21}} > & < \boldsymbol{r_{22}} > & \cdots & < \boldsymbol{r_{2}k} > \\ \vdots & & \ddots & \\ < \boldsymbol{r_{n1}} > & < \boldsymbol{r_{n2}} > & \cdots & < \boldsymbol{r_{nk}} > \end{bmatrix}$$

The relative closeness of each normalized material value r_{ij} to the ideal solution A^+, considering the material and its associated AM process, is calculated according to Eq. 23:

$$C_j^+ = \frac{S_j^-}{|S_j^+ + S_j^-|}, \quad 0 \le C_j^+ \le 1,\ j = 1, \ldots, M. \qquad (23)$$

where Si^+ (Eq. 24) is the minimum Euclidean distance of the requirement of the material j from the ideal solution, and S_j^- (Eq. 25) is the Euclidean distance of each requirement stringency level from the anti-ideal solution.

$$S_j^+ = min\sqrt{\sum_{j=1}^{n}(r_j - r_j^+)^2} \quad i = 1, \ldots, M \forall r_j \le r_j^+ \qquad (24)$$

$$S_j^- = max\sqrt{\sum_{j=1}^{n}\left(r_j - r_j^-\right)^2} \quad i = 1, \ldots, M \forall\forall r_j \ge r_j^- \qquad (25)$$

Thus, if $C_j = 1$ then $r_j = A^+$ (ideal solution) and if Cj=0, then $r_j = A^-$ (anti-ideal solution). Therefore, the conclusion is that the alternative a_i is closer to A^+ if C_j is closer to the value of 1 [28].

III. RESULTS

Once the global stringency levels are calculated, applying the Eq.21, the following matrix is obtained (Fig.8). Note that the first row represents the calculation for small batches (SB) or ad-hoc manufacturing and the second row (i-index of r_{ij}) for the production in large batches (LB). The columns provide the r_{ij} value for every material and AM process as indicated in Table 19.

$$\begin{array}{cc} \begin{matrix}\text{SB}\\ \text{LB}\end{matrix} & \begin{bmatrix} 0.57 & 0.57 & 0.59 & 0.69 & 0.73 & 0.51 & 0.61 & 0.61 \\ 0.41 & 0.62 & 0.67 & 0.50 & 0.86 & 0.41 & 0.51 & 0.75 \end{bmatrix} \\ & \begin{matrix}\mathbf{1a} & \mathbf{1b} & \mathbf{1c} & \mathbf{2a} & \mathbf{2b} & \mathbf{3a} & \mathbf{3b} & \mathbf{3c}\end{matrix} \end{array}$$

Materials/Process designation according to Table XIX
a) Mechanical and electro-mechanical applications
(Categories 1, 2 and 3)

$$\begin{array}{cc} \begin{matrix}\text{SB}\\ \text{MP}\end{matrix} & \begin{bmatrix} 0.50 & 0.50 & 0.45 & 0.55 & 0.83 & 0.55 \\ 0.36 & 0.53 & 0.53 & 0.55 & 0.94 & 0.34 \end{bmatrix} \\ & \begin{matrix}\mathbf{4a} & \mathbf{4b} & \mathbf{4c} & \mathbf{4d} & \mathbf{5a} & \mathbf{5b}\end{matrix} \end{array}$$

Materials/Process designation according to Table XIX
b) Electrical applications (categories 4 and 5)

FIGURE 8. **Matrixes showing r_{ij} for small and large batches criteria. a) Mechanical and electro-mechanical applications and b) Electrical applications.**

TABLE 19. **MCDM analysis using small batch production criterion.**

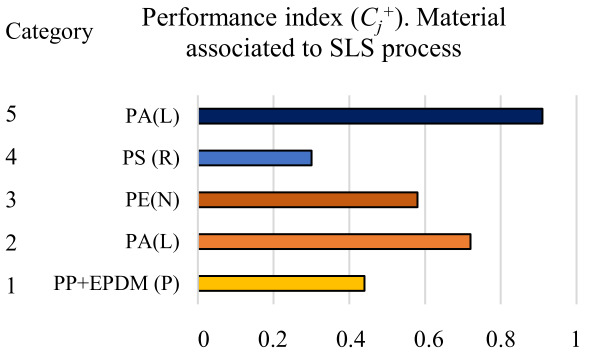
Category		Material ↔ AM Process	r_j	S_j^+	S_j^-	C_j^+
1	1a	PMMA (B) ↔ FDM	0.57(SB)	0.43	0.16	0.27
	1b	PMMA (B) ↔ SLS	0.62(LB)	0.38	0.21	0.35
	1c	PP+EPDM (P) ↔ SLS	0.67(LB)	0.33	0.26	0.44
2	2a	PC (M) ↔ FDM	0.69(SB)	0.31	0.19	0.38
	2b	PA (L) ↔ SLS	0.86(LB)	0.14	0.36	0.72
3	3a	PC (M) ↔ FDM	0.51(SB)	0.49	0.10	0.17
	3b	PE (N) ↔ FDM	0.61(SB)	0.39	0.20	0.34
	3c	PE (N) ↔ SLS	0.75(LB)	0.25	0.34	0.58
4	4a	PE (N) ↔ FDM	0.50(SB)	0.50	0.14	0.22
	4b	PE (N) ↔ SLS	0.53(LB)	0.47	0.17	0.26
	4c	PP+EPDM (P) ↔ SLS	0.53(LB)	0.47	0.17	0.26
	4d	PS (R) ↔ SLS	0.55 (LB or SB)	0.45	0.19	0.30
5	5a	PA(L) ↔ SLS	0.94(LB)	0.06	0.60	0.91
	5b	IR(Q) ↔ FDM	0.55(SB)	0.45	0.21	0.32

Note: for the calculation, r_j^+ is, in this case, equal to 1. Whereas, r_j^- is lower bound determined by the minimum value obtained in their applicable category of application (1 to 5 according to Table I).

Using Eqs. 23 to 25, and considering the production based on small batches versus the production in large batches, Table 19 shows the calculation of the relative closeness to the ideal solution (C_{ij}^+) used as a performance index.

TABLE 20. **Summary of the potential combination of material and AM process for the intended application in harsh environments.**

Material	AM process and the optimal production strategy	Application Category	Performance index (C_j^+)
PMMA (B)	FDM (SB)	1	0.27
	SLS (LB)	1	0.35
PA (L)	SLS (LB)	2	0.72
	SLS (LB)	5	0.91
PC (M)	FDM (SB)	2	0.38
	FDM (SB)	3	0.17
PE (N)	FDM (SB)	3	0.34
	FDM (SB)	4	0.22
	FDM (LB)	3	0.58
	FDM (LB)	4	0.26
PP+EPDM (P)	SLS (LB)	1	0.44
	SLS (LB)	4	0.26
IR(Q)	FDM (SB)	5	0.32
PS (R)	SLS (SB/LB)	4	0.30



Note: In the case of PS(R), the performance index is equal in both small batch and large batch cases.

FIGURE 9. **Performance index for each category of application, showing the closeness to the ideal solution.**

On the other hand, Table 20 provides a summary of the different alternatives of processing for each selected polymer.

In general, it can be concluded that SLS along with a strategy of production based on large batches is the best option to use AM routes to process some of the selected materials, if their performance indexes are evaluated by categories. Thus, Fig.8 shows the performance indexes (by category) of the best options of materials to be processed using SLS route.

A. ACCORDING TO THE SUITABILITY OF MATERIALS FOR SLS TECHNIQUES

PP+EPDM can be a good option to manufacture mechanical heavily stressed components such as cams, gears, couplings, racks or rollers.

PA can be a good fit to manufacture components of bearings, guides or valves. In addition, PA can be also used to manufacture films and sheets for electrical applications. In fact, as Fig.9 exhibit PA is a much better alternative to manufacture electrical components (category 5). PE would be a good option for high voltage insulation in magnet coils, high voltage switchers or transformers. Finally, PS would be used in radio frequency and microwave applications. All these alternatives allow to use SLS processing routes, being able to be applied not only to produce small batches but also large batches of production.

B. ACCORDING TO THE SUITABILITY OF MATERIALS FOR FDM TECHNIQUES

Several materials are more suitable to be processed using FDM techniques, these are the PC, PE e IR. Whereas PC is suitable for application categories 2 (mechanical) and 3 (electromechanical). The solution closer to the suitable scenario is to manufacture category 2 applications ($C_j^+ = 0.38$) in small batches.

PE can be used for applications of categories 3 and 4 and to work with small or large batches. Nevertheless, the solution with the most performance index ($C_j^+ = 0.58$) is the category 3 (elecro-mechanical) for large batch production.

Finally, IR is suitable for FDM techniques using a small batch production strategy.

IV. CONCLUSIONS

A methodology for selecting a combination of polymers and their associated AM routes has been presented, solving the binomial consisting of materials performance for the intended application and the most suitable manufacturing process. Physical features such as mechanical, thermal and electrical properties and radiation tolerance features have been analyzed.

Applying the SL methodology along with different MCDM concepts, the best option performing the analysis by application category, is the SLS AM technique since allow work with large batches. Thus, the materials selected for this processing technique are as follows:

- PP+EPDM can be a good option to manufacture mechanical heavily stressed components.
- PA can be a good fit to manufacture friction components. PA can be also used to manufacture films and sheets for electrical applications.
- PE would be a good option for high voltage insulation.
- PS would be used in radio frequency and microwave applications.

On the other hand, FDM techniques are more suitable to process several materials, as their performance indexes in Table 20 provide. These materials are the PC, PE e IR. Thus, PC is more suitable to manufacture category 2 applications in small batches. In addition, PE should be used in the manufacture of category 3 (electro-mechanical) applications considering large batch production. Finally, IR is suitable for FDM techniques using a small batch production strategy to manufacturing category 5 applications.

The methodology developed in this paper exhibits relevant results that allow us make a decision about the best combination of polymer and AM process. In the future, this methodology and obtained results will be used to improve the screening tasks of materials and process selection that are performed previous to the experimental testing.

LIST OF SYMBOLS AND ABBREVIATIONS

A_{ij}	Requirement *i* specified by the materials specification *j*.
A^+	Ideal solution
A^-	Anti-ideal solution
CERN	Conseil Européen pour la Recherche Nucléaire
C_j^+	Relative closeness of each material requirement R_{ij} to the ideal solution A^+
d_i^+	Separation between the requirement *i* specified by the materials specification j (A*ij*) and the ideal solution according to the constraints
d_i^-	Separation between the requirement i specified by the materials specification j (A*ij*) and the anti-ideal solution according to the constraints
DS	Dielectric Strength
EL	Elongation
EMI	Electromagnetic interference
EPRI	Electric Power Research Institute
FDM	Fused Deposition Modeling
HRD	High radiation dose
IAEA	International Atomic Energy Agency
IRSD	Irradiation resistance for soft damage
IRSED	Irradiation resistance for severe damage
LB	Production in large batches
LOCA	Loss of coolant accident
L_s	Value provided by the requirement of the analyzed material
$L_{s(max)}$	Maximum value of requirement provided in the distribution made up from all analyzed materials
MCDM	Multicriteria decision-making methodology
MES	Melted electrospinning
MFC	Total manufacturing cost per part
MRD	Medium radiation doses
MTC	Material cost
PA	Polyamide
PE	Polyethylene
PMMA	Polymethylmethcrylate
PP+	
EPDM	Polypropylene ethylene polyallomer
PS	Polysterene (R)
r_{ij}	Normalized stringency level
r_{j}	Mean value of r_{ij} for the materials specification *j*.
RPV	Reactor pressure vessel
RR_j	Radiation levels that cause pernicious effects
RR_{normal}	Radiation resistance at normal conditions
RR_{acc}	Radiation resistance at accident conditions
RT_{normal}	Radiation threshold calculated for normal operating conditions
RT_{acc}	Radiation threshold calculated for accident (LOCA) conditions

S_j^+	The minimum Euclidean distance of any requirement of the materials specification j from the ideal solution
S_j^-	The maximum Euclidean distance of any requirement of the materials specification j from the anti-ideal solution
SB	Small batches/ad-hoc manufacturing
SL_{ij}	Stringency Level of the requirement i of material j
SL_j	Global Stringency Level of the material j related to physical properties
$SL'_j.$	Global Stringency Level of the material j related to radiation resistance
$SL_{(max)}$	Maximum value of Stringency Level according to the defined scale
SLM	Stringency level methodology
SLS	Selective Laser Sintering
SMR	Small modular reactor
T_{max}	Maximum continuous service Temperature
TS	Tensile strength
α	Lineal thermal expansion Coefficient
K	Thermal conductivity
ρ	Volumetric resistivity

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