PROJECT FINAL REPORT

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Executive summary

Rapid manufacturing provides several key advantages over traditional manufacturing processes, most obviously by removing the need for part-specific tooling, which for prototypes small runs is a substantial advantage. The STEPUP project focuses on the Selective Laser sintering (SLS) process, seeking to extend the range of mechanical properties available in SLS-processable materials, particularly to produce stiffer materials whilst maintaining other desirable properties such a surface finish and strength. The key methods by which SLS-processable polymers can be enhanced is by creating composites based on materials with good SLS-processability. Both stiff, ceramic fillers (or similar) of various geometries and stiffer polymers have been considered as additions into standard material for SLS. The aim is to improve mechanical and thermal properties through

- Structural modification involving a currently widely used polymer like PA12;
- Alloying at the nanoscale with different polymers to tune mechanical properties;
- Nanocharging the polymers to further enhance and meet user requirements and specifications.

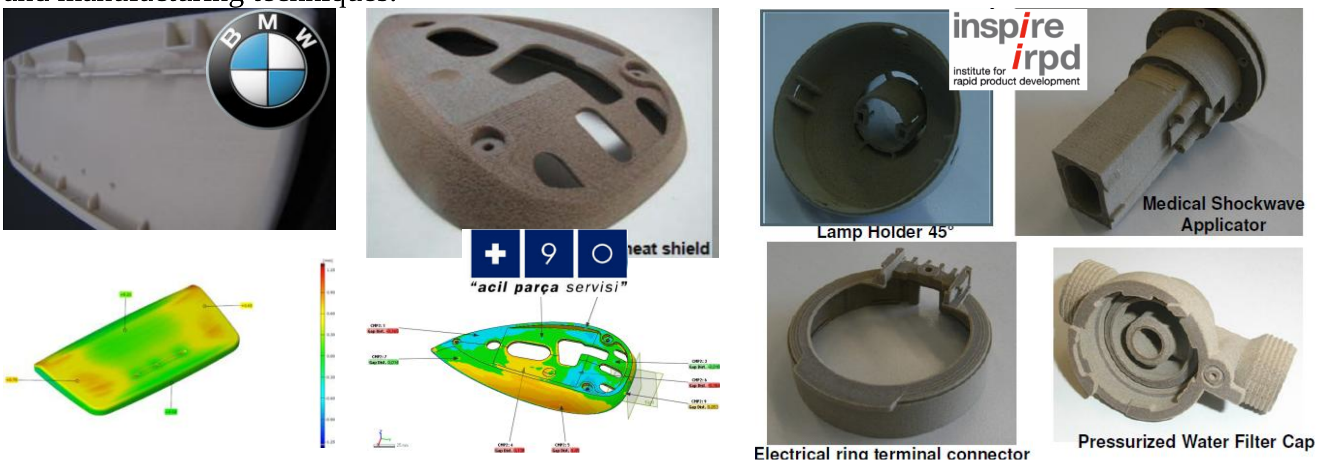
The main development areas are related to:

- Material design by identification of criteria determining the experimental boundaries
- Processing of nanostructured polymer materials as nanopolymers, polymers alloys, or nanocomposites by high energy ball milling technique (HEBM).
- SLS process to adapt currently used industrial machine to the new material concept generated
- Laser Sintering of parts having improved properties to widen application window for automotive, medical instrumentation, consumer goods

Main results achieved are the

- **Establishment of new cost effective synthesis route** to produce polymers nanocomposite that can be processed by SLS having
- **design methodology including software and modeling tools** for predicting the performances of SLS nanomaterials and identifying the best SLS candidate to replace a reference materials
- **off-line processability methodology** to understand the basic behavior of SLS processability
- **parts obtained by SLS** with the material variants selected with good accuracy and surface quality

Three demonstrative applications in the automotive, consumer goods and instrumentation sectors, have been chosen to demonstrate the possibility of substituting and replacing conventional products and manufacturing techniques.



The mechanical property measured show enhanced behavior above 60°C. The accuracy of the sintered parts covers the requirements and the benchmark parts were produced successfully with process costs identical to the commercial process. The potential price calculated for the STEPUP material looks very promising. The material impact can be very high, if the results of the recycling rate are as expected and the final part properties can be verified with different material lots on different machines. This will result in a replacement of existing materials as the price of the material is the most important hurdle for further impact of additive manufacturing. This development could result in an increase of applications in the worldwide market of additive manufacturing, as the price is decreased compared to currently available materials.

Project context

In the last two decades more than 30 different Layer Manufacturing (LM) Technologies or “Additive Processing Technologies” based on different technological principles was developed. The most promising ones have been engineered to a higher level and are used for the production of prototypes, parts or models in a huge number of applications. . Some state-of the-art review articles give a distinguished overview of the LM techniques

Nowadays LM technologies are divided into rapid prototyping (RP) and rapid manufacturing (RM) depending on end use. RP means the production of prototypes, visual design aids and test parts. RM stands for production of real production parts (end products). Especially for RM applications SLS is one of the most promising technique and subject of STEPUP project.

One drawback of an increased utilization of SLS for RM is the small number of polymers applicable Mainly Polyamide 12 (PA 12), as well as pure polymer or compounded with different additives (e.g. glass beads and fibres, aluminium powder) is used today in commercial systems in noteworthy amount. The fillers are usually present in bigger fractions (e.g. 30-50%) to influence the matrix properties in the desired manner.

Facing the material side there is an obvious need and a big chance for new SLS materials.

Either new polymeric matrix materials or new compounds of existing systems are conceivable. One prominent example is the recent introduction of PEEK polymer into the SLS technology. Another approach are so-called ‘nano compounds’ for SLS

Often this technology is compared to currently used injection moulding process for mass production So for the definition of the targeted SLS material properties of plastic parts produced via injection moulding are the primary benchmark. A comparison of the main features of SLS process and injection moulding (IM) is given in Figure 1.

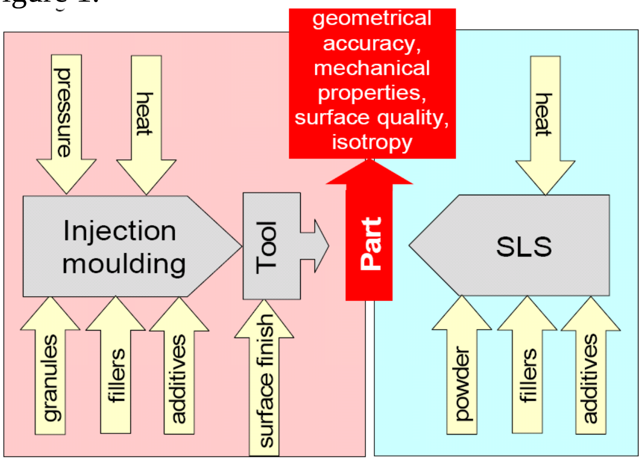


Figure 3: Comparison of main characteristics of Injection Moulding (IM) and SLS;

The main difference between both processes is pressure used in IM to compact the material in the viscose condition. This ends up in connection with an IM-tool with parts having on the one hand outstanding and isotropic mechanical properties and on the other hand an almost perfect geometrical accuracy in combination with a good surface quality.

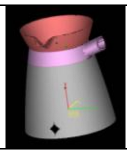
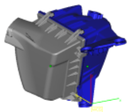
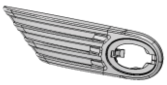
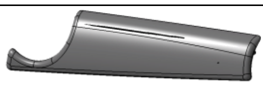
SLS compared to IM parts exhibit usually a 30-50% loss on mechanical side, a distinct anisotropy in different spatial direction due to the layer-wise production and a high material consumption (main portion of the powder is just aged whilst SLS process but not transferred into a part). Furthermore crystallisation could not easily be controlled in SLS, thus sometimes thermal distortions (curling) prevent a refined accuracy

3.1 Objectives

The project is focused on development of new composite materials for existing SLS prototyping machines to produce parts and products in small to medium sized batches for a wide range of possible applications. The science / technology objectives of the project are as follows.

- Material design by identification and establishment of criteria placing restrictions on prospective experimental materials. These include material performance, life cycle considerations, and regulatory boundaries.
- Development of new nanostructured materials based on PA as either nanopolymers, alloys with other polymers, or nanocomposites.
- Agglomeration of (20µm-100µm) nanophased (10nm-20nm) particles suited for RM via SLS.
- Parts having improved properties to widen application window for automotive, medical instrumentation, consumer goods. For the definition of targeted mechanical properties materials usually subjected to injection moulding was used as benchmark. It came out that for all investigation fields of application parameters like E-Modulus, elongation at break, impact strength must be improved.

In terms of specific applications, the technical objectives of the STEPUP project are defined by the desired properties of parts which the project partners wish to be able to make. Each application is demanding in different ways.

Case study	Image	Description
Shockwave applicator (Inspire)		Component housing, holds electrical components (shockwave reflector, PCBs) and carries cooling water at 1bar. Must resist 5kV shock. Minimize cost and volume per unit of strength
Water filter cap (Inspire)		Filter housing for domestic water system. Must withstand water at 60°C and 10bar, approved for water contact. Minimize cost and volume per unit of strength
Domestic iron heatshield (+90)		Shields user and upper part of iron from hotplate. Must be a thermal insulator and resist 150°C. Minimize cost per unit of stiffness and minimize heat loss from rear of heatplate.
Coffee pot collar (+90)		Connector between coffee pot, spout and handle. Must withstand water at 100°C and approved for water contact. Minimize cost per unit of strength and stiffness
Intake muffler (BMW)		Air intake housing (under bonnet). Resistant to temp (120°C), fuel, oil, salt water. Minimize mass and cost per unit of stiffness
Side scuttle (BMW)		Exterior trim, clips into chassis. Dimensional stability. Surface finish and scratch resistance important.
Faceplate panel (BMW)		Dashboard, instrument panel. Resistant to temp (100°C), dimensional stability. Surface finish and scratch resistance important. Minimize mass and cost per unit of stiffness

The introduction of **nano capabilities** and material properties modification is a never before implemented research with breakthrough potentials in parts performances. This is shown in Figure 2 which indicates also the predicted properties improvements, which will bring polymers growing up in properties in the direction of metals (die casting).
Unique physical, mechanical, electrical, and thermal properties induced by the interaction of the polymer with the particles and the state of dispersion can be obtained.
This approach allows to **extend the formulation possibilities** using also incompatible charges from low to high concentration.

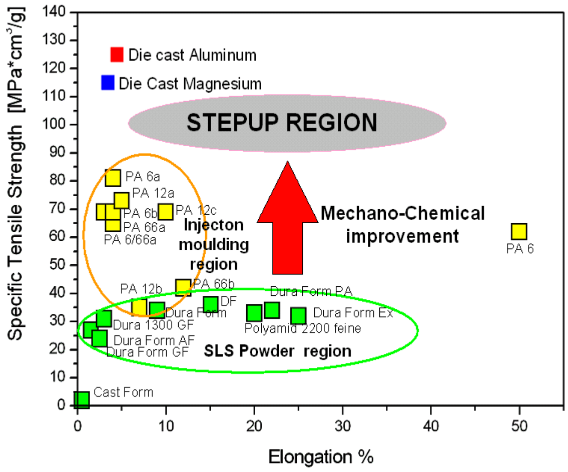
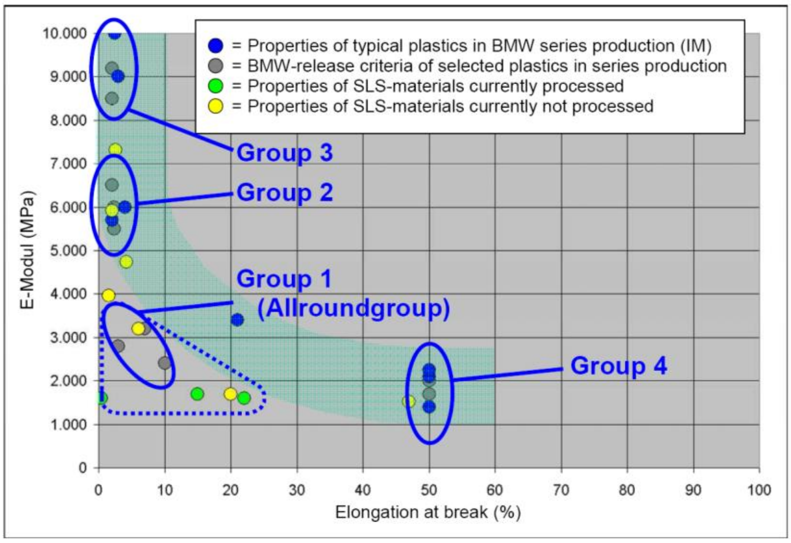


Figure 2: predicted properties improvement

The development of new SLS materials, especially ‘nano compounds’ with enhanced properties, is the main target of the present project. During the project setup three technical regions was identified as the main strategic approach: automotive parts, consumer goods and medical instrumentation.

Automotive applications (BMW)

Vehicular components require polymers with enhanced mechanical properties in particular. Project partner BMW analysed the principle used SLS materials in comparison to IMmaterials and their internal release criteria. Figure 4 summarizes the data of E-modulus versus Elongation at break for those materials.



Vehicle components require a part with a Young's modulus of 4 - 6 GPa, tensile strength of 60 - 80 MPa, and failure strain of 20 - 30%. Best figures for SLSed PA12 are around 1.3 GPa, 30 MPa, and 5%, respectively, so substantial improvement is required in all respects. Stiffness is mostly a material property, while tensile strength and failure strain are profoundly influenced by both material mechanical properties and processing. Beside the enhanced mechanical properties temperature resistance above 70°C is requested. Moreover from the automotive point of view further primary requirements for SLS materials are: - smooth and colored surface (without paint), - chemical stability to sweat and suntan lotion, - chemical stability to motor oil, brake fluid and fuel), - thermal stability, - long term stability, dimensional stability with and without heat, - heat, -light, -UV, -ageing and fatigue resistance, - low price.

Consumer goods application (+90)

Regarding the analysis of project partner +90 consumer goods SLS materials will be in competition mainly with standard plastics like ABS, PP and PC and its alloys. These plastics are commonly used in household, sports and recreation products this day. This means from the mechanical point of view, if SLS materials will compete with standard plastics, the targeted STEPUP materials have to have a high elasticity and impact resistance as parts should not be brittle at all.. Besides the mechanical properties consumer parts from future SLS materials have to outperform the actual standard SLS materials regarding some further physical and part properties as summarized as follows:
Food safe materials Dimensional accuracy Surface quality Resistance to cleaning chemicals
Any advancement in these fields of properties would be a great success for STEPUP materials although this could not be defined with precise data like mechanical properties.

Medical Instrumentation (Inspire, irpd)

From the medical point of view also the mechanical properties of SLS materials has to be enhanced regarding tensile strength and elongation at break. A similar analysis as performed from BMW regarding the actual materials and their properties is given in Figure 5 where the actual available SLS materials are confronted with typical Injection moulding materials.
It can be seen in a pronounced manner in this illustration of 'Tensile Strength' versus 'Elongation' that SLS is clearly separated from IM materials (yellow vs. blue dots). Figure 5 give also an indication which region is unoccupied from SLS materials now (red ellipses) and which gaps must be filled not only to be competitive with IM of medical applications.

Other Properties

Besides the pure mechanical properties an enhancement of SLS materials in order to realize improved physical properties, refined part properties and eased processing with less material waste are highly appreciated as well and targeted in STEPUP.
Enhanced physical properties which may come up with STEPUP project are materials with improved electrical conductivity e.g. for electronic parts or advanced heat absorption materials for a simplified SLS processing or even magnetic materials for the production of magnetic parts and magnetic structures with complex geometries.
Regarding refined part properties materials which generate SLS parts with smoother surfaces for a simplified part finishing are highly appreciated in the SLS community as well as materials with less material waste. This means to improve the cycle-number where the same SLS-powder could be subjected to the SLS process without gaining a negative influence on the processability of the materials (e.g. generation of orange peel).
If the newly developed STEPUP materials support a homogeneous crystallization of SLS materials to reduce or even prevent thermal distortion of parts during the processing and subsequently induce a higher isotropic behavior between the single layers a further step-up is realized in STEPUP for improved SLS material.

3.2 Main S&T results

The innovation chain established in the project STEPUP include different aspects from the material design and modeling, to the polymer processing and post treatment up to the SLS process development and production of prototype parts. All these stages have contributed to create and assemble a manufacturing chain among the project partners that will be exploited beyond the STEPUP. The main S&T results achieved that are described in the report follows the development areas and WP subdivision of the project:

1. material design including: Virtual Material Design, software tool for prediction of nanomaterials properties, Composite synthesizer, material substitution tool. (WP1 and WP2)
2. Database of composition, manufacturing conditions and properties of all polymer systems (WP1)
3. polymer processing by high energy ball milling technique and post processing treatment to obtain SLS powders (WP1)
4. Materials selection methodology (WP1)
5. Off line processability methodology to have a fast screening of materials properties; (WP1 and WP2)
6. SLS process development (WP3) and characterization to select the most promising material variants
7. Parts development and testing to obtain the demo parts targeted in the project.

1 Material design

Materials selection has been performed keeping into account not only the results obtained from case study definition but also from the modelling activities and experimental results that gave inputs for the iterative selection of systems.
Materials selection has been articulated at different levels:

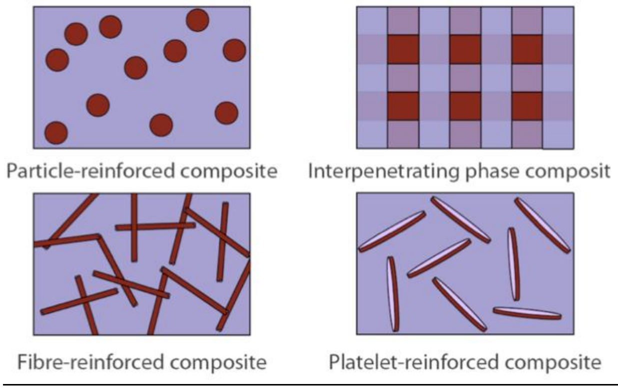
- Modeling and materials design;
- Software and database for materials selection;

1.1 Nanocomposite Modelling (WP2)

During the first period, the experimental matrix has been designed by MBN in order to screen a wide variety of polymer families (100 variants). Different synthesis strategies have been applied to develop and produce different classes of nanocomposite materials by high energy ball milling process as shown in the figure below.
The aim is to improve mechanical and thermal properties through:

- Structural modification of current PolyAmmide polymer;
- Alloying polyamide and other polymer matrix (at the nanoscale) with different polymers to tune mechanical properties and especially elongation at fracture;
- Nanocharging the polymers to further tune and meet user requirements and specifications.

Predictions of mechanical behaviour have been performed following different mathematical models, implemented in the software, specifically developed by UCAM for nanomaterials used in the project. Each model is based on phase geometry of the composite. Though with quantitative results have not been possible, the literature has made it clear that particulate polymer composites will fail at lower stresses than the matrix, and that this depends upon the degree of particle dispersion, with uniform dispersion resulting in the strongest composite. IPCs have been found to be capable of exceeding the strength of the weaker element by up to a factor of two in a regime that is relevant to the polymer composites at hand here. Several possible new types of composite that may overcome limitations in



existing designs have been proposed on the base of this modelling.
All the predictions produced a ranking of each type of composite, where possible, in terms of mechanical stiffness, failure behaviour, and SLS processability. The design methodology and software tools for predicting the performances of SLS nanomaterials and identifying the best SLS candidate to replace a reference materials have been developed and implemented in the software enabling virtual materials to be considered as part of optimal material design project. This allows a vast number of potential and speculative compositional variations to be investigated without the need of costly manufacture and characterization trials. All major "classic" phase geometries have been considered for particles including the expected failure mode, particles with dendrites, fibers with "plates" on the ends and isotropic fibers and "active" particles for overcoming the problem of continuity of reinforcement across granule boundaries.

The systems studied fall within the processability boundaries considered in the projects:
Dispersed stiff particles. Even for totally rigid filler, a filler volume fraction of about 0.4 would be needed to stiffen the matrix. Strength is maximized when the stiff particles are evenly dispersed, with a substantial decrease in strength accompanying clustering. Failure for composites with a large difference in moduli between the phases usually fail by loss of phase coherence. Since particles are essentially point-like on the scale of the powder granules, provided they are uniformly distributed throughout the granules then a powder-reinforced polymer composite is perfectly compatible with SLS.
Interpenetrating phase composites. IPCs are unusual in that the composite strength can exceed the strength of the weaker component. The strength of such a composite reaches a maximum when one phase is much stronger than the other, with the quotient of the phase strengths equal to the quotient of the moduli. Even if it is assumed that a polymer with a suitably high modulus and low melting point to provide adequate reinforcement has been found, there still remains the issue of how to ensure adequate "matching" of like phases between granules so that an IPC is formed after sintering. It is not currently clear whether this will prove a significant challenge—simply mixing together granules of "pure" powders of each polymer may, for instance, suffice—but its difficulty may be expected to be very sensitive to the relative volume fractions.
Isotropically oriented fibres. If such a composite could be made isotropic and homogeneous then a filler fraction of 3%-6% of alumina-stiffness fibers would produce a composite with stiffness in the most demanding 4 GPa–6 GPa range. These fractions increase in roughly inverse proportion to the fiber stiffness. Using the current SLS technique, isotropically oriented fibres will always leave a thin-walled network of unreinforced polymer throughout the sintered sample. Much of the predicted advantage of such composites would thus be lost.

In all cases composite moduli would be significantly impaired if after SLS processing it remained significantly porous. In such cases the filler fractions would have to increase substantially to compensate, though it would be expected that fibre composites would be less sensitive to porosity than particles composites. For equivalent volume fractions and the same constituent materials, isotropic fibers are usually between two and five times stiffer than dispersed stiff particles or concentric shells, which are similar. Due to material constraints, IPCs cannot be equivalently ranked. All other things being equal, IPCs offer the best failure behavior, probably followed by isotropic fibers, and finally dispersed stiff particles / concentric shells. Overall, dispersed stiff particles / concentric shells are most suited to SLS processing, followed by IPCs, with isotropically oriented fibers the least suited.
From the modelling the following indications have been arisen that would have been matched with the manufacturing capabilities and constrains of the production and sintering techniques considered in the project:

Vehicle components. Within the framework of continuum mechanics, isotropic dispersed particle / concentric shell composites based upon PA12 cannot achieve the minimum 4 GPa stiffness required for this application unless perfect sintering of a 40 % filled polymer were achieved. In practice filler fraction would need to be higher to allow for porosity. The impact of such a high level of filler (even if it could be achieved) would be to cause failure at a low strain level, and certainly to eliminate the long, tough, "tail" of the stress-strain diagram for pure PA12: the required elongation at failure of 20 %–30 % would not be approached. This approach would only be practical if some significant "nano-effect" / "non-continuum effect" were demonstrated.

An IPC would be an excellent candidate for this application either if polyester liquid crystal was sinterable along with PA12 or if another suitable polymer could be identified. It would attain the required stiffness with around 30 % polyester liquid crystal, though as that material fractures at only about 30 % strain it is unlikely that the composite would last beyond about 4 % strain. Despite this problem, since this geometry is fairly compatible with SLS processing, if a suitable polymer *could* be found this approach would be promising.

An isotropically oriented fibrous composite could easily meet the stiffness criteria if it were uniform, but in order to achieve this the SLS process would require substantial modification to allow much longer diffusion times. No method for estimating the strength or the elongation at failure has been identified. Before considering modifying the SLS process (undoubtedly a major undertaking) the failure behaviour would require more consideration.

Overall, particle composites seem unlikely to deliver the required performance. Isotropic fibrous composites would require modification of the SLS process, but (apart, perhaps, from elongation at failure) should answer the specification. IPCs are perhaps the most promising, but their performance depends upon identifying a suitable polymer with very unusual properties: the candidate identified in this work seems non-ideal in terms of failure behaviour, and is unproven in SLS. Two possible avenues for progress exist.

Consumer goods. Achieving a modulus in the region of 500 MPa is not a problem; in fact, *any* of the phase geometries and indeed perfectly sintered PA12 should answer this aspect of the specification. Quality of surface finish is more a feature of processing than material, upon which the authors defer to those with expertise in this area. This application appears to make stronger requirements on processing than materials.

Medical instrumentation. This specification is hard to make recommendations for, concentrating as it does on hard-to-predict quantities at failure. However, it is important to note that perfect PA12 itself fulfils all of the criteria specified, suggesting that—as for the "consumer goods" specification—achieving this specification is more a matter of adjusting the processing than altering the processed material.

One aspect of the work undertaken in this project has been to model the impact of plasticity in the matrix on the properties of a particle composite. This has been developed from a three-dimensional finite element (*FE*) model which predicts the elasto-plastic response of particulate composites:

- Inputs of the model: experimental uniaxial response of the polymer, elastic properties of the particles, reinforcement volume;
- Output: uniaxial stress-strain curve of the composite to be compared with experimental data;

The model has proven capable of predicting the uniaxial response of particle composites: an example comparison graph between experimental and numerical results is shown in figure.

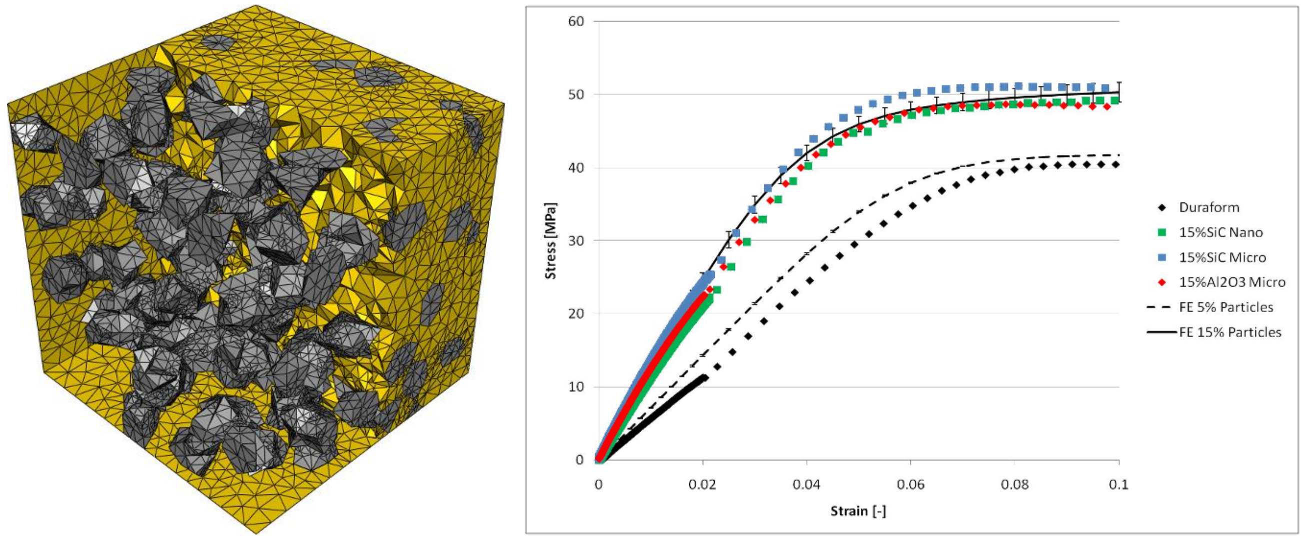


Figure: The grid used for running the FE model with 15 % volume fraction of particles - Comparison between the FE results and the experimental stress-strain curves.

It is clear from these results that this elasto-plastic modelling produces good agreement with experimental results obtained to date. Given the role of porosity in SLS processed samples it is likely that this would also have to be considered if the approach is used more widely.

1.2 Software tool for prediction of nanomaterials properties (WP1&WP2)

As it is widely recognized that 80% of the environmental footprint of a product is determined at the design stage, this work has focussed on developing a design methodology and workflow that enables designer to evaluate the environmental performance of their products in the early stages of design.

Predicting materials properties is a key factor for new materials development. A series of new tools have been developed following a design methodology to achieve a quick and simple first simulation prior any detailed study. Two main tools have been developed:

- Composite synthesizer which calculate the performance of virtual materials by extracting data from project database and predicting performance of user defined nanomaterials using algorithms specified by the selected model plug-in;
- The Materials substitution tool which identify possible candidate substitute for given reference material for a specific application;

Composite synthesizer has been designed by GRANTA, using models provided by UCAM, to explore the potential of hybrid materials, emphasizing the choice of components, their configuration and their relative fractions. Indeed the components will be involved by the choice of materials to combine the configuration by the shape and connectivity of the components, their relative volumes by the volume fraction of each component and the scale by the length scale of the structural unit.

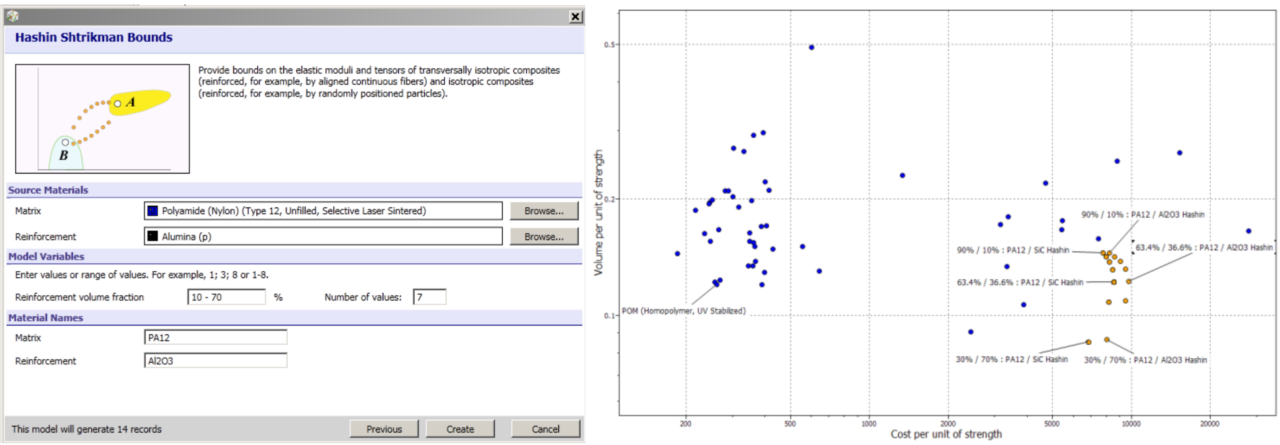


Figure 5 – Chart to explore combination of new materials

The synthesizer uses continuum and micro-mechanical models to estimate the equivalent properties of each configuration. This can be plotted on material selection charts, which become comparison tools for exploring unique combinations of configuration and material (figure 5).

The material substitution tool has been developed as an expert tool to identify possible candidate substitutes for a given reference material for a specific application. The tool, integrated in an enhanced MI, ranks the potential replacement materials based upon key criteria specified by the user in order of closeness. It also identifies any potential problems with the substitution such as a lack of data or a property significantly different to the reference material.

The drivers of this functionality could be summarized as follow:

- Development of new innovative materials as substitutes for a current material in product design, e.g. looking for the closest SLS material to the reference material currently in use;
- A need to find alternatives if the current material has become too expensive;
- A need to find alternatives to withdrawn or hard to source materials;
- To identify replacements for obsolete or ‘at risk’ materials (restricted substance, excessive carbon footprint);

The ranking of potential replacement materials is based on criteria selected by the user from the properties available in the database. These criteria can be classified in three categories:

- “Must-have” criteria with respect to reference material: proposed materials must have properties better than reference ones;
- “Must-have” criteria which differ from those of the reference material: proposed materials must have characteristics required but not present in reference ones;
- “Nice to have” criteria, where the goal is to get as possible to the reference material;

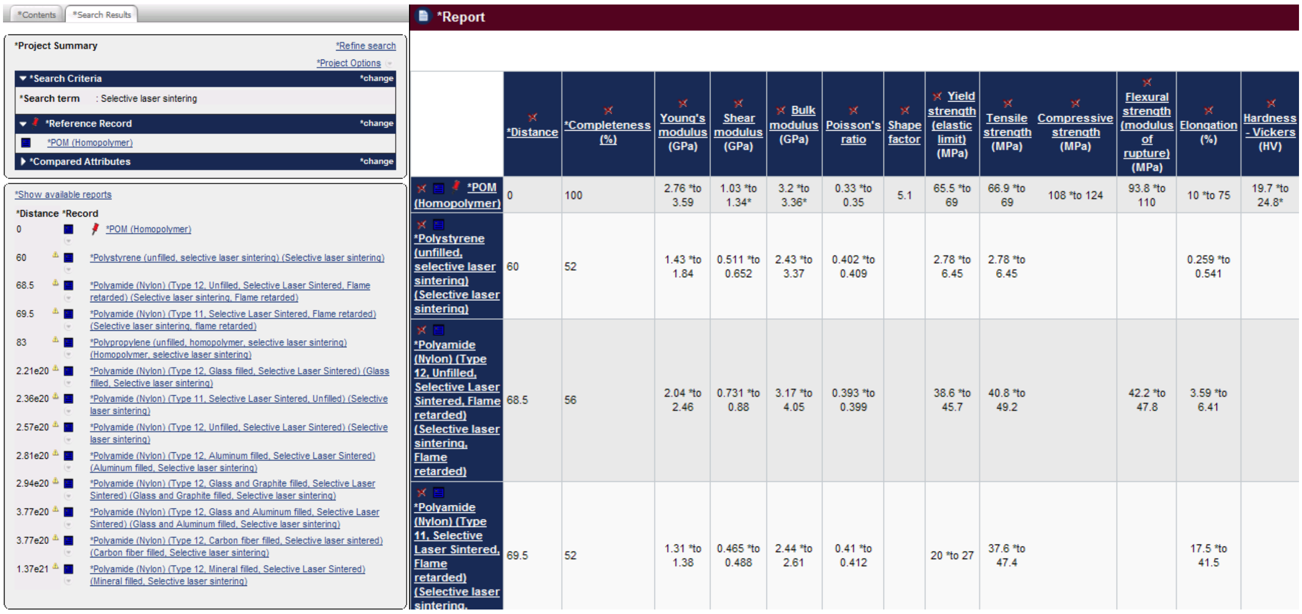


Figure – Selection of group of properties.

The ability to turn Substitution Tool on/off, depending on license, has been introduced after a case by case approach study. Data on commercial SLS polymers for a future commercial database have been collected and EcoAudit tool has been updated. A design methodology and software tools for predicting the performance of SLS nanomaterials and identifying the best SLS candidate to replace a reference material have been developed enabling virtual materials to be considered as part of an optimal material design project. This allows a vast number of potential, and speculative, compositional variations to be investigated, without the need for costly manufacture and characterization trials.

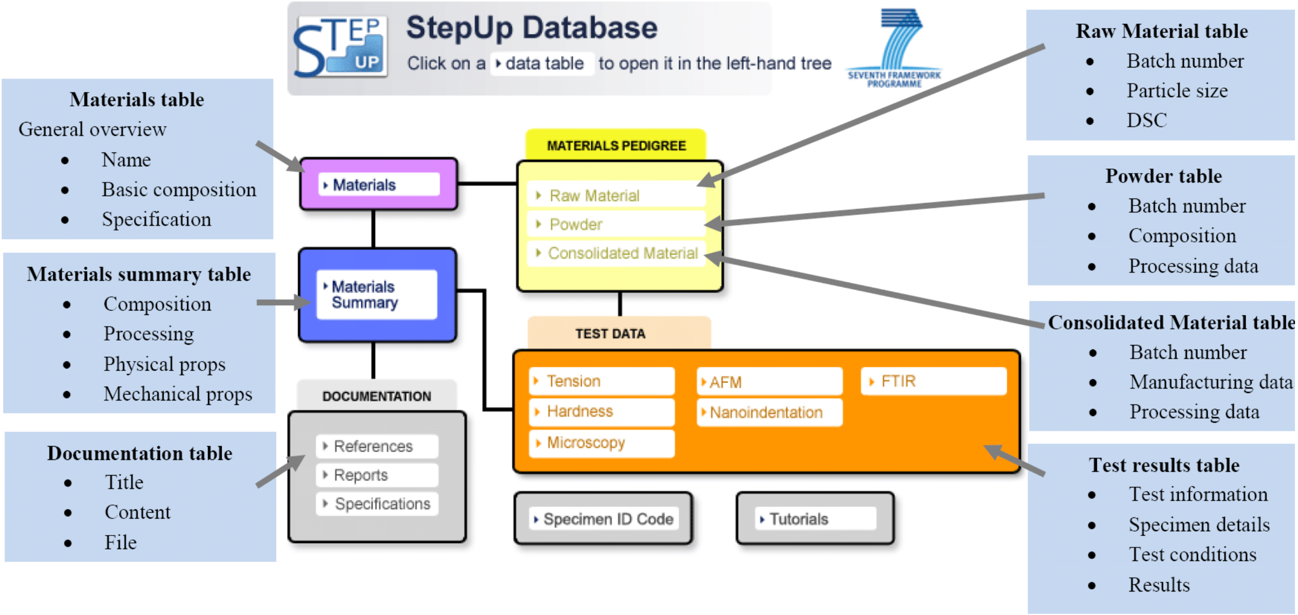
2 Database of composition, manufacturing conditions and properties of all polymer systems

The StepUp project has produced a lot of data related to the processing of SLS samples and associated tests performed on them. These data have to be stored, shared and analysed by the partners of the project from different countries. As a result, the database is being populated with the results of the different partners. It is an ongoing process as characterization and tests are still in progress.

The database is divided into five main tables; materials, materials pedigree, test data, material summary and documentation, with each table storing different types and levels of information. Each table is linked to others as shown, so as to minimize redundancy and to ensure that full traceability of all data is maintained.

The main entry point to the database is the Materials table, which gives a high level overview of the materials. Users can then navigate directly to the Materials Summary table, which stores ‘technical datasheet’ level summaries of the materials developed by the project. Alternatively, if users are interested in the detailed pedigree, they can navigate to the Materials Summary table via the Materials Pedigree (powder & consolidation) and Test Data tables.

The figure below represents the map of the database. The relational structure is ensured by links between tables (illustrated by black lines on map).



StepUp database schema

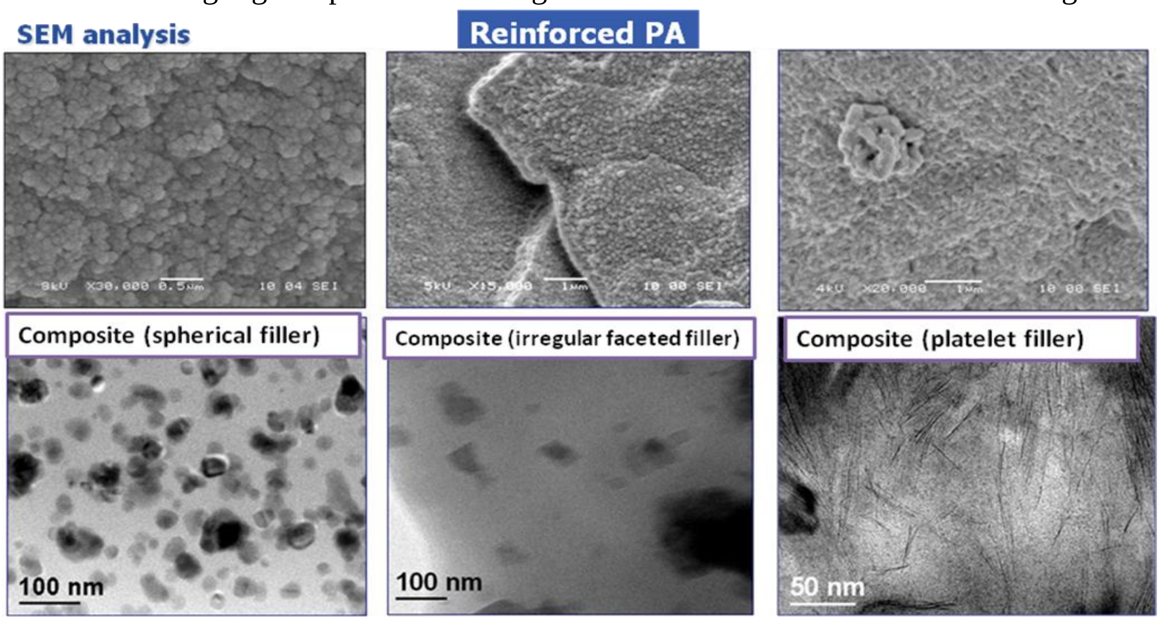
Granta Design has designed, developed and implemented an online database for the StepUp project that enables all project partners to store, view, analyse and disseminate processing and test information on materials being developed in the project.
The implementation was divided into two parts:

- Building the database structure and workflow to suit the needs of the consortium
- Setting up the database infrastructure to enable online access to the database.

Following this implementation, a significant amount of data has been generated by the project partners and imported into the database by Granta Design. The database will continue to be populated as long as new nano systems and tests will be carried out and will become a comprehensive and advanced source a data for nanomaterials.

3 Polymer processing by HEBM and post processing technique (WP1)

The HEBM synthesis strategies applied originated different powder variants and micro-nano structures having high disperse and homogeneous characteristics as shown in the figure.



It has been found that synthesis process does not change the thermal properties of the base polymer and materials processed by HEBM have suitable chemical characteristics to be processed by SLS.
Initial material selection has been performed keeping into account materials requirements defined in case studies, ecological impact of the final material and compatibility of base polymer with SLS process. An effective synthesis route took into account the selection of raw materials also in order to potentially reduce the projected cost of overall process and material. So initial granules of polymers have been used and processed until a fine and homogeneous distribution of the filler into the polymer matrix is obtained. The high potential of this route is related to the fact that can be basically applied to all the thermoplastic polymers and therefore offer an high flexibility in terms of starting material matrix and filler selection.

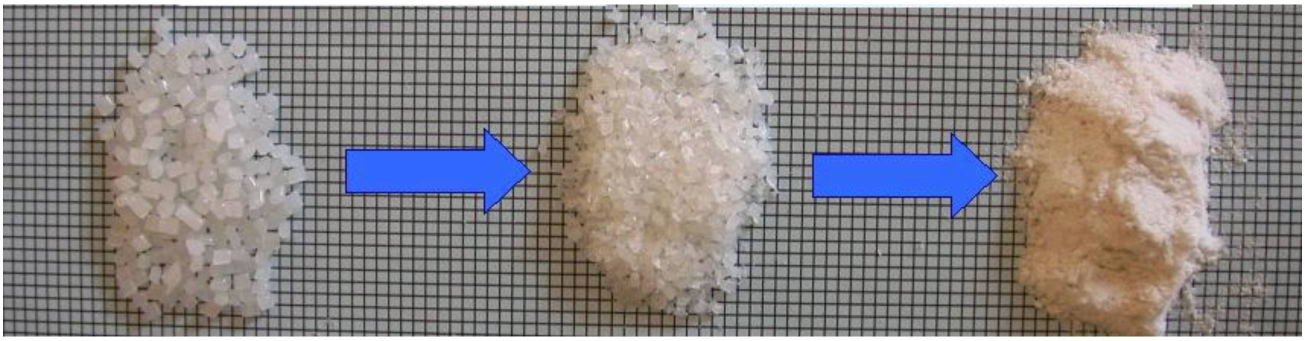


Fig pellets after conventional polymer milling and HEBM process

The initial bottleneck of powder shape and morphology hampering the processability of polymer has been deeply studied and investigated. In order to achieve good flowability properties suitable for SLS process, MBN investigated several post processing techniques to round the particles produced by HEBM.

A wide range of rounding processes have been considered and tested, such as mechanical, thermal, thermo- mechanical and chemical surface based treatments. An effective methodology has been found to produce rounded particles with particles size suitable for SLS process therefore SLS processability was improved. The output yield of rounding process is about 90% while the production rate is in line with the synthesis process output.
As shown in figure the particles are spherical and the filler distribution formerly originated by the HEBM process is kept in the final polymer.

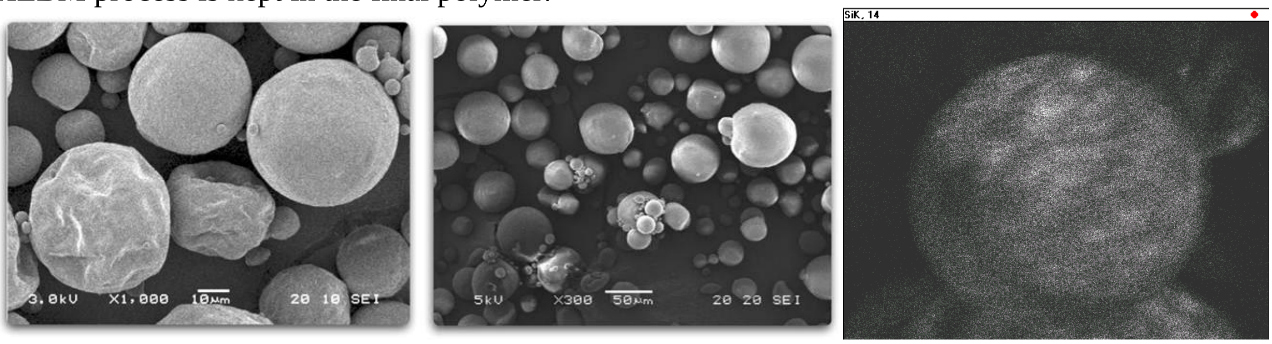


Figure: rounded polymer particles produced. Distribution of nanofillers inside the particle (right)

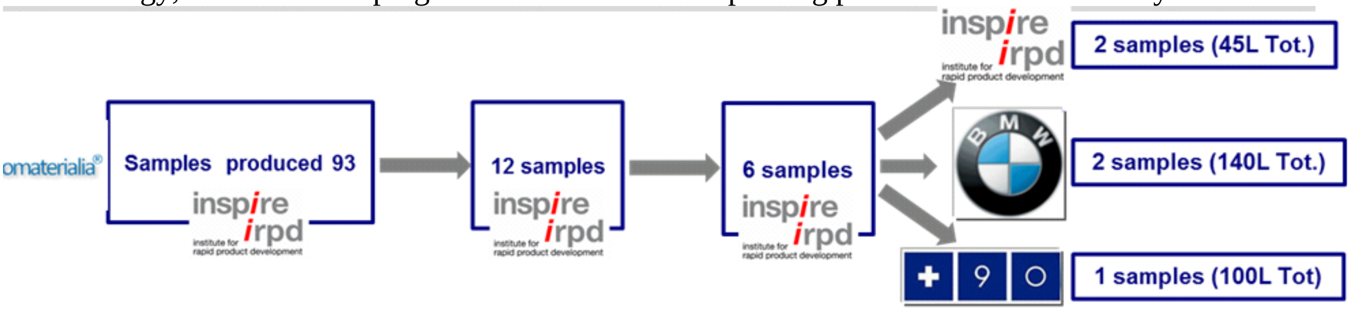
For this reason rounding process was apply to post process and round polymer powder The approach consists in process the nanocomposite polymer in a solvent and then produce the spherical particles. In rounding process, the solution/dispersion of nanocomposite particles (produced by HEBM) to instantly producing spherical particles (like a drop).

Mechanical properties of the developed materials variants have been initially investigated on consolidated injection moulding specimens by a laboratory extruder and shaped in bone like samples. Injection moulding consolidation on the powder produced by MBN in relation with virgin polymers and commercial grade. Information like consolidation aptitude, operating temperature, viscosity fluctuations on the base of charge size and content have been achieved.
In agreement with modeling output it was found out that the best mechanical properties are achieved when the polymer PA12 base is processed with other compatible polymer grade. The presence of nanofiller in the polymer matrix does not produce a strong nanoeffect in terms of mechanical properties.

1. High Energy Ball Milling (HEBM) is an effective technique to obtain new polymer based material with improved properties
2. Powder developed in the project by HEBM and rounded by Rounding exhibits suitable SLS behavior compared with all the other powders tested.
3. The nanodispersion achieved at powder level (SiO_2 in PA12 matrix for instance) after HEBM is retained after rounding post treatment
4. This route is an effective way to round and shape polymer based powder after HEBM process to obtain suitable powder for SLS and to achieve a good quality of components
5. The production capacity of SLS powders by HEBM + rounding can be estimated at several ton/year.

4 Materials selection methodology (WP1)

Materials selection has been performed keeping into account not only the results obtained from case study definition, but also from the modelling activities, and experimental results that gave inputs for the iterative selection of systems.
At stage 1 many variants of polymers and nanocomposites were produced with different formulations and processing parameters. Preliminary tests were executed for selecting processes conditions, milling methodology, and for developing suitable devices for improving process control and safety.



Phase / Name	I / Basic Material	II / Basic processing	III / Process development	IV / Process security
Equipment/Work	Powder / Polymer Analyses	SLS micro-sampling facility	SLS equipment	SLS equipment
Material amount	m ≥ 50 ml	m ≥ 2 liters	m ≥ 20 liters	m ≥ 100 liters
Comments	Analysis of - Thermal prop. (DSC, TGA) - Powder fluidity - Grain size distribution - IR-Absorption	1 shot on micro-sampling facility: - Powder rolling behaviour - Reduced built volume: - 100x100x50 mm → 6-9 tensile bars (max.)	1 shot optimization of machine/process parameter for regular machine setup: - heat up/ build temperature - part cake behaviour (cracks) - Laser energy - divers (see Inspire protocol)	Repeated processing: - Recyclability of powder - Repeatability of process - scaling - process map - enhanced characterisation
Result (expected)	Go/Nogo regarding basic material properties	Go/Nogo regarding basic processing; property trends	Machine/process parameter acknowledge; basic characterisation	Process transfer to production (fit for Industry); PRO/CONTRA-list
Correspond to WP	WP 1 (Task 1.5-2) WP 2 (Task 2.1-1)	WP 1 (Task 1.5-3) WP 2 (Task 2.2-1) WP 3 (Task 3.1-2)	WP 3 (Task 3.1-2) WP 3 (Task 3.2-1) WP 4 (Task 4.1-3)	WP 4 (Task 4.2-1) WP 4 (Task 4.2-2)

The polymer nanomaterials were submitted to the cut off screening of SLS sinterability test. The screening, consisting in complete range of characterization techniques performed on powder and consolidated material to determine if the specific nanosystem has the required properties to fit with SLS process requirements as well as final properties.
The process of evaluation of a powder material regarding SLS suitability has been designed and performed stepwise according to the material development strategy. The workflow for the development of new SLS powders is applied for StepUp project and as it can be seen in figure
Phase I: Determination of basic powder properties;
Phase II: Evaluation of basic powder behavior (e.g. roll on) on the SLS system; in case of less material (m < 10 l) a recently developed "micro-sampling facility" can be applied;
Phase III: Evaluation of basic sintering parameter regarding test protocol
Phase IV: Optimization regarding part processing, part properties; Repeatability of process; Recyclability of powder; process transfer (fit for Industry);

During the first period, the experimental matrix has been designed in order to screen a wide variety of polymer families (100 variants). Samples have been produced first in a small scale to test their processability properties**.** In the subsequent stages the most promising materials after the on-line SLS processability and SLS trials have being produced to perform preliminary and optimisation tests. This "on-line link" between the initial stages (evaluation of basic materials properties and basic processing) and the following ones (process development and optimization) is necessary to achieve all the information for the best selection of the 3 project demonstrators.

5 Off line processability (WP1)

The comprehensive processability of polymer powders by Selective Laser Sintering (SLS) depends on a huge amount of different and occasionally interacting parameters. The development process is usually divided into phases:

1. Determination of basic powder/material properties;
2. Evaluation of basic powder behaviour on the SLS system ;
3. Evaluation of basic sintering parameter;
4. Optimization regarding part processing, part properties; repeatability of process; recyclability of powder; process transfer ('Fit for Industry');

Once a new material system is produced it is crucial to understand the basic material properties regarding SLS processability. For this reason in the frame of the project a new off line method has been developed based on characterization of the most relevant material parameter and their SLS specific physical behaviour:

- **Thermal properties**: The thermal behaviour of a SLS material determines the whole temperature management of the SLS equipment. TGA analysis allow to know the decomposition temperature and thus the temperature stability of the material.
- **Energy absorption** (ability of laser radiation absorption): During the isothermal sintering process the polymeric material on the SLS equipment is put to a certain stable temperature close to the melting temperature. In order to absorb the radiation energy in effectual amount the material has to have a certain absorption coefficient. Also curl phenomena (thermal distortion) can be avoided by correct laser energy absorption;
- **Rheology:** A high flowability of polymer melt (low zero viscosity) and low surface tension is necessary for homogenous parts produced by SLS. The Melt Flow Index (weight of a polymer melt which can be pressed through a defined die with a certain load and at a certain temperature) gives an indication about the processability and, more important, the viscosity change during

processing (polymer aging). This method failed for polymers filled with (inorganic) additives for very low amounts of fillers loaded.

- **Particle and powder:** The flowability of powder depends on shape and distribution of particles, surface energy, electrostatic and some more. A simple approach to access the flowability of powders is the determination of bulk and tap density. Determination of bulk and tap density gives a good indication on the one hand regarding powder density which is correlated with the final part density and on the other hand regarding the flowability by calculation of the so called Hausner ratio HR. This HR-value is used to make a 'go', 'nogo' decision in this off-line selection approach.

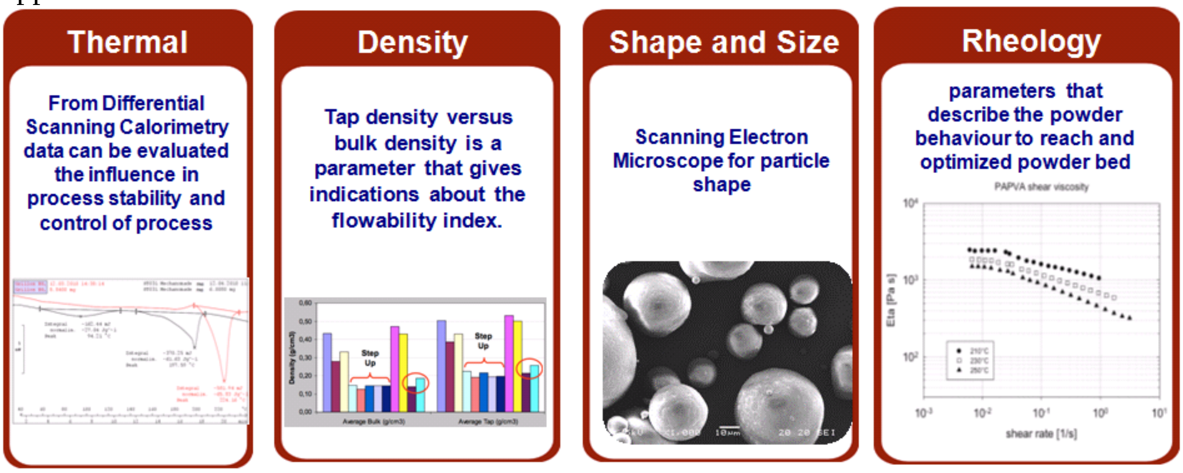


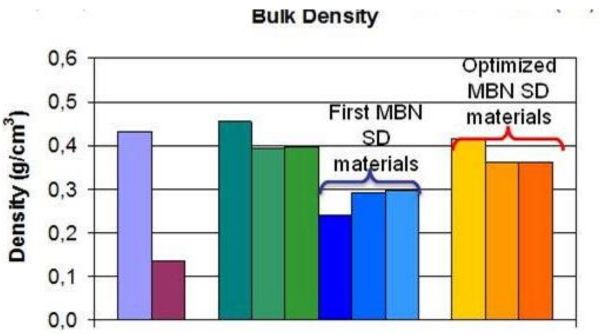
Figure 7. Outline of "Off line processability" methodology

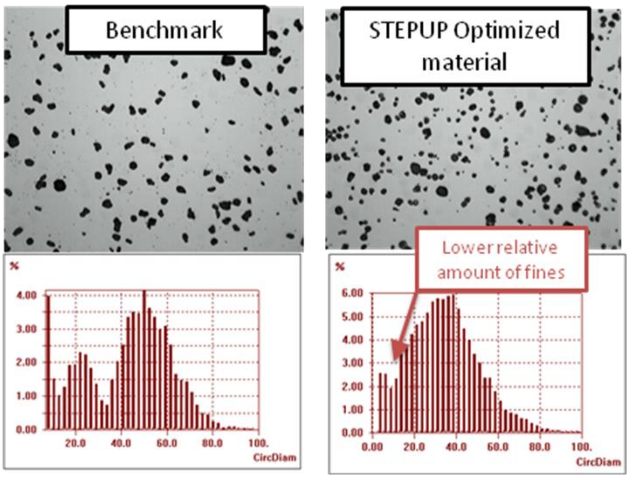
It has been found out that that principle processability is mainly determined by:

- **Basic Polymer:** in addition of polymer samples based on standard SLS polymer powder other polymers matrix exhibited suitable processing properties for SLS;
- **Particle profile:** this is the most important factor for the powder behaviour during processing and it is almost independent from physical material properties; the formation of a well-shaped powder bed without giving SLS processing failures is particle profile (shape) dependent;
- **Fillers**: the influence of type and amount of filler on the SLS processing is not as high as the influence of the basic polymer. But when filler quantity is too high (> 10%) problems may occur;
- **Polymer viscosity:** charging polymers with nanoadditives cause a dramatic increase of viscosity

Selected systems with a likely potential were analysed intensively regarding their powder properties as a pre-step for SLS trials. A new evaluation system was applied for this reason for the first time for SLS dedicated powders and could be demonstrated as a powerful tool. Based on these analytical steps selected nanopolymers are then subjected to SLS trials with a home developed 'Micro Sampling Facility (MSF)' to get a more refined assessment of processability under 'production near' conditions. This off-line selection approach leads to preliminary 'go', 'no-go' decisions for the initial screening and the selection of the most promising materials. Main findings on polymer obtained are the following:

- Annealing post process has a positive effect on enhancing the allowable sintering window;
- Improved processing range of PA12 compared to PA12+ nano platelet. This confirms the presence of a filler affects negatively the processing range;
- Regarding the density, reproducible results with the rounding technique can be obtained; besides presenting a good flowability condition, the bulk/tap density obtained has been considerably improved than previous set of rounding materials;
- Reproducible batches are obtained and thus a constant powder quality is achieved with distribution improved regarding benchmark material.



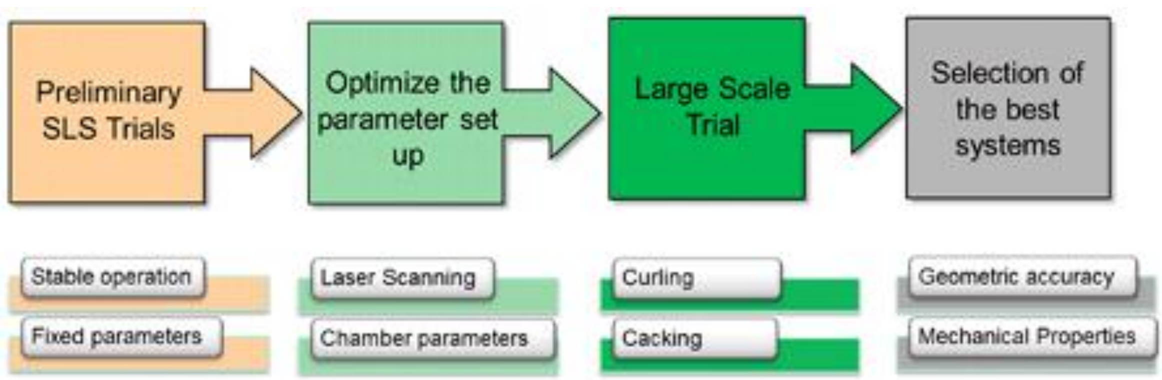


The preliminary selection of materials on the base of sinterability and processability led to the following 12 variants of polymers that passed to stage 2 of experimental matrix:
- polymer nanocomposite with round filler: PA12L + SiO_2 (3 variants),
- polymer nanocomposite with platelet filler: PA12 L + Nano platelet and PA12L + Mica
- polymer polymer alloys (IPC): PA12 + PEEK (3 variants), and PA12 + PVA
- PA12 polymer matrix (no addition): PA12 (2 variants)
- PP polymer matrix (1 variant)

6 SLS process development (WP3)

To set the proper parameters to be able to process the material by SLS, a systematic procedure for the appraisal of new STEPUP materials has been developed. This procedure has been adapted for working with small amounts of powders, particularly to reduce the number of necessary evaluation tests as possible. Defined step:

1. Defining within the range of possible parameters, those which are more sensitive for the process stability and also related to the sintered part density degree. Being an extremely complex process, the selection of this set of parameters is based on the experience and know-how of inspire irpd;
2. Defining a parameter value set, considering the previous off line processability test results and perform the sintering test.
3. Related to an optimized condition already reached, this step takes care of specific targets or set of properties that need an improvement (sintered density, surface quality, dimensional accuracy)



This criterion deals with overcoming typical process problems:

- Curling: lifting of layers due an uneven surface temperature distribution;
- Streaking: formation of clumps or powder agglomerates;

- Short feed: low amount of recoating materials due an irregular powder packing density;
- Bed cracking: associated to a high powder bed heating rate;

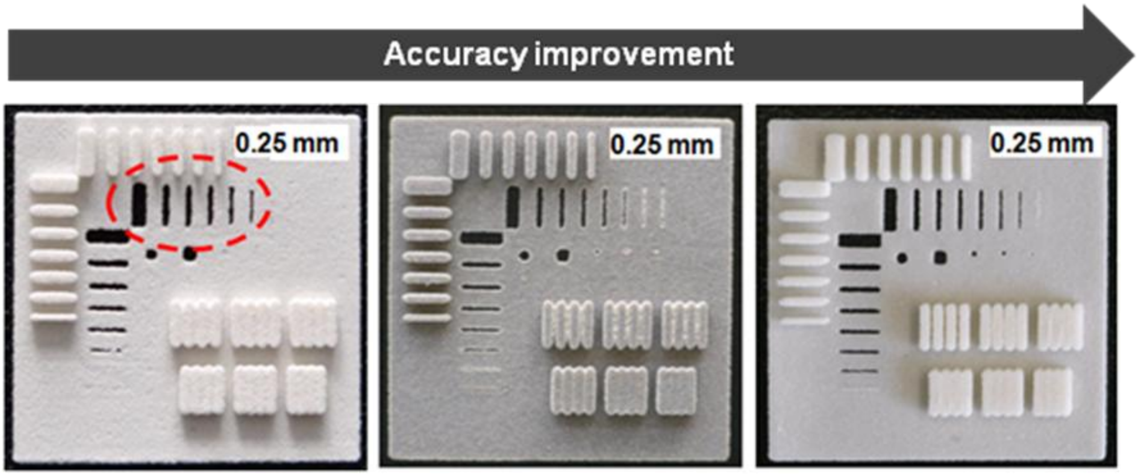
The development of new suitable SLS materials, due the complexity of the process and the large amount of variables and setting parameters involved, requires to carefully distinguish and correlate the most representative variables that influence each phase of the process with the particular phenomena observed.

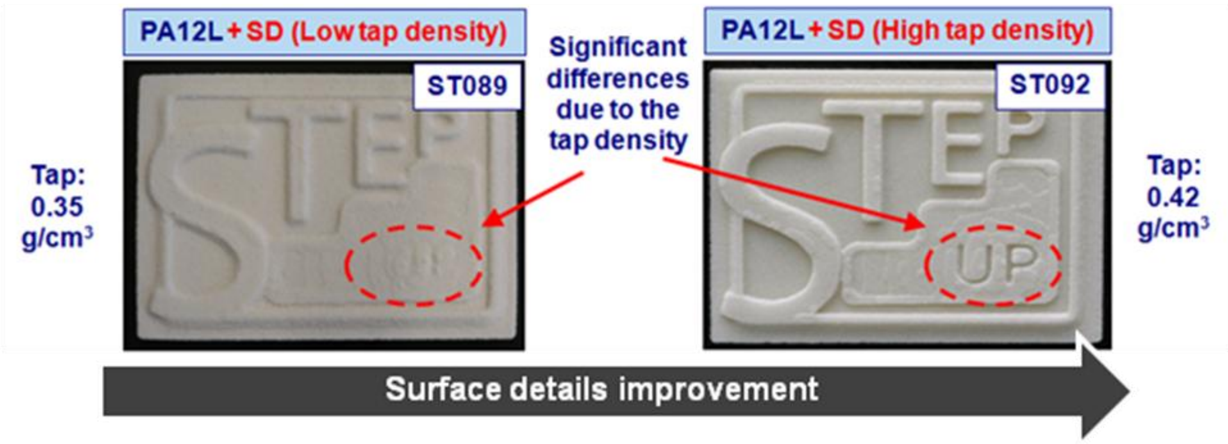
Regarding the surface quality and dimensional accuracy, a clear difference between parts built with and without post processing step can be observed. The surface porosity was considerable reduced and the geometrical detail definition was improved. it can be stated that post treated powders exhibit a low porosity surface. Therefore, the rounding process was defined as a needed step during the whole powder development cycle.

In general, the curling effect was not present, which is one of the main difficulties to overcome to achieve the stability criterion.
Tests to define optimized process parameters in order to improve the parts regarding their properties and geometry definition have been performed:

- The laser power is a critical factor in relation to the final part density that can be achieved: higher values are restricted due material thermal decomposition;
- The part bed temperature set up permits to achieve a curling free sintering surface during the build. Higher values are constrained due the appearance of “part caking” and a faster materials ageing cycle for the un-sintered powder;
- The roller speed is related to the powder deposition. Higher values permit to achieve a faster recoating cycle and thus a faster build but it can lead to the appearance of cracks, which generate instabilities of the support powder during the build. Also part bed density is influenced by this parameter;
- The feed ratio permits to adjust the amount of material employed for each powder side container. A reduced amount of material is desired in order to employ as less materials as possible during the build.

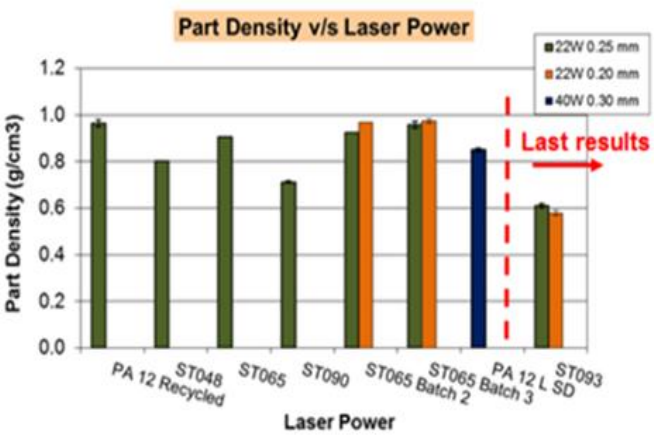
Due the employment of the micro sampling facility (MSF) that allowed the use of a reduced amount of material the powder bed isn’t homogenous. This behavior is correlated to a very good flowability of the rounded powder, which is highly desirable for an SLS material.
The critical problems observed in the preliminary SLS trials have been overcome. The powder particles geometry and size distribution, improved by rounding post processing treatment, lets to achieve an adequate packing density and high surface recoating quality. The accuracy improvement and surface details was correlated with the enhanced material powder characteristics and sintering properties.

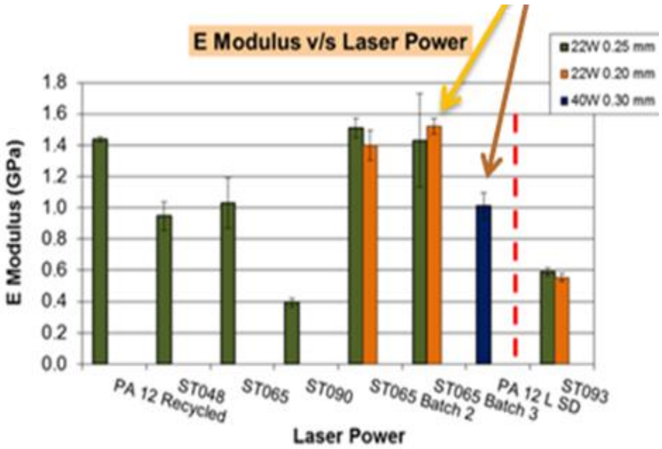




The SLS trials performed on larger scale gave reproducible properties both from morphology appearance and mechanical properties.

The tensile results show a continuous improvement due to the intensive research and development of the previous powder engineering stage. This is reflected on the enhancement of the part density and elongation at break of the neat polymer (PA12), which actually achieves a value over 8%, improving also the ultimate tensile strength over 30% in comparison to the first generation of nano-filled materials. Also, as this material constitutes the polymer matrix, the effect of the nano platelet nano-filler is confirmed by an average elastic modulus increment of 40%.





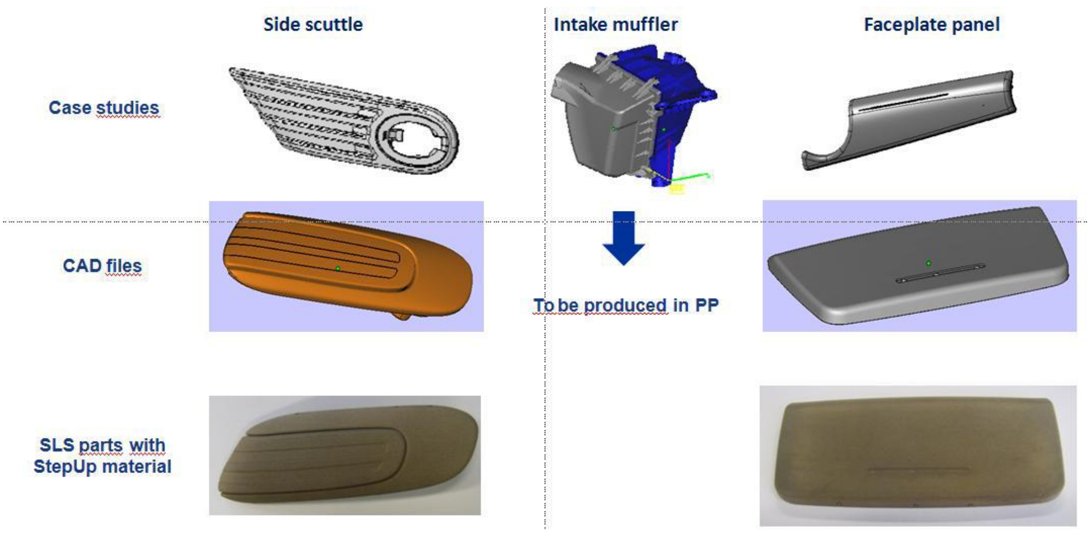
The selection of the best performing subset of materials based on processability test and sinterability mainly led to the following materials for the prototype activities:
1-PA12NC : best E modulus but with lower elongation at break
2-PA12: lower E modulus but with higher elongation at break
3-PP matrix (ST093) has much room of improvement (addition of reinforcement) thanks to the larger processability window: selection has not been finalized on this material

Parts development and testing (WP4)

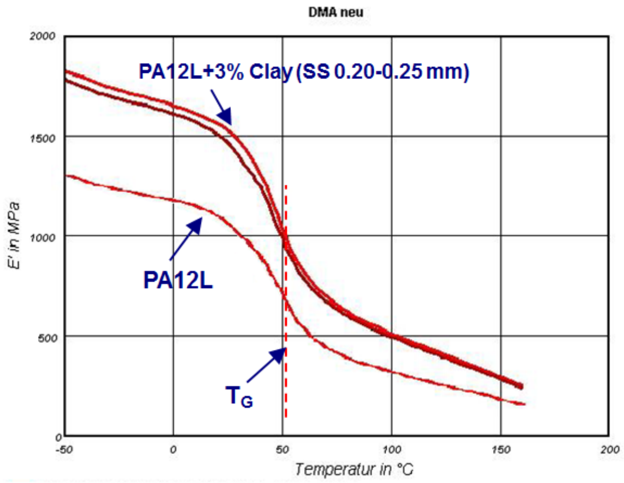
Rapid Manufacturing process chain has been adopted in commercial SLS equipment, the development of additional powder handling and sintering strategies has been performed in order to set up the process for the new mechano-made SLS powders.
The SLS equipment considered for testing operate with a C02 laser, presenting build platforms with an effective build volume of 300mm (diameter) x 200mm and 340mm x 340mm x 620mm respectively. Both systems allow building parts under different laser scanning strategies and chamber temperature conditions, which can be adjusted to a certain extent to process new materials without extreme further modifications. Despite the concept similarities between both manufacturers, main differences can be observed regarding the internal powder handling system and the powder heating procedure.
For 3DSystems, the powder recoating is achieved by a counter rotating 50 mm diameter roller and for the EOS a fixed blade moves with powder inside The recoating stage is a very critical step during the whole sintering process and powder flowability plays therefore a vital role. Thus, the materials behavior is investigated employing both machines to analyze the effect of potential discrepancies among both systems. Additionally, 3DSystems equipment allow preheating the powder to a defined temperature previous its deposition on the central build platform, which results beneficial to avoid a high undercooling of the sintered cross sections. Therefore, the risk of building unwanted curling or warpage is reduced, particularly when new materials with a comparative reduced temperature window are expected. In case of EOS equipment, this preheating stage is not present, which remarks the need of testing employing this kind of equipment as well, since currently they cover an important market share.
The two STEPUP materials that are considered for testing and both are based on PA12 grade. The natural grade and a filled version (3% v/v nano- platelet) were selected for the upscale production (batch amounts of at least 10 kg are considered) according to the encouraging results obtained during the preliminary research activities using the micro sampling facility developed at Inspire. Both materials present to date the best powder packing and flowability characteristics among the whole set of polymer-polymer and polymer-metal compounds developed.

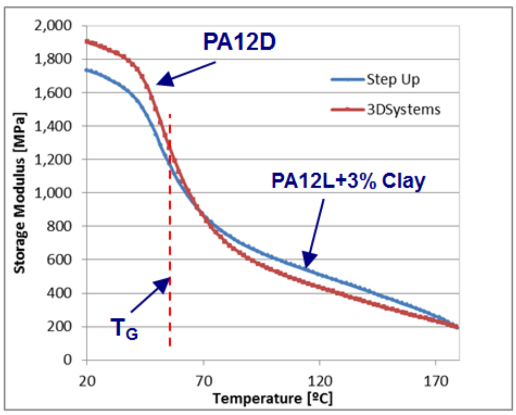
Production phase

The introduction of new materials forces a revaluation of process by considering the benchmarks employed, the manufacturing route defined and the final technical analysis performed. The powder produced with the best SLS performance and improved mechanical properties, in comparison to the unreinforced polymer matrix, corresponds to PA12 reinforced.
The industrial SLS test for automotive parts was performed at BMW facilities. The machine employed was an EOS P380. Regarding the preparation of the build process and in order to save material the aim was to set up a flat build including “temperature crosses”, tensile bars, notched bar impact test specimens, DMA specimens and the ashtray lid (BMW Demo) representing an interior application in a vehicle.



Once produced the pure PA12L presents values that are considerably below the reinforced polymer using the nano platelet filler. The difference results particularly interesting above the glass transition point. For instance, at 100 °C, the storage modulus of the composite material achieves a value of 500 MPa, which is 67% higher than the unreinforced version that achieves a modulus of approximately 300 MPa.



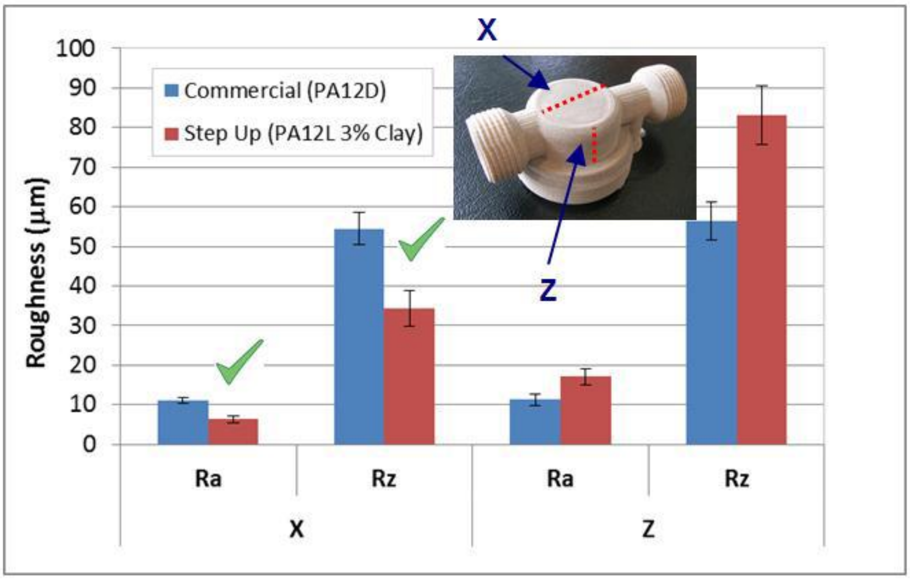


Moreover it can be noted that below the glass transition point, 3DSystems PA12 presents a higher value in comparison to Step Up PA12-Platelet, but this difference continuously reduces as the temperature increases. Indeed, above 60ºC approximately, both curves cross and Step Up PA12 3 % Platelet presents a higher resistance until the melting point is reached. Normally, the operating range for polymers is set below the glass point to avoid the considerable reduction of the stiffness. However, many commercial applications request that materials can adequately withstand up to 100 ºC and this new material offers to customers an improved solution to their claims while maintaining basically the same polymer matrix.

The industrial SLS test for medical parts was performed at INSPIRE facilities. The raise up of previous sintered layers and curling at different locations on the part bed surface was, as written in precedent chapters, a critical issue. The presence of this phenomenon is related to the shrinkage of the layers due to the crystallization behavior. For this material (PA12L with 3% of nano platelet), the thermal processing window is reduced and thus the crystallization and melting points are closer to each other in comparison to the commercial material Duraform PA. Additionally, the SLS machines currently on the market have a non- localized temperature control over the sintering surface that is not accurate enough to avoid this warpage effect on the whole surface. A recent study performed by

Wegner & Witt (2011) showed that an inhomogeneous powder bed is generated by the IR heater and differences up to 7 °C across the horizontal surface can be obtained. This study reveals that the current state of the art on temperature controlling is not suitable for working with small sintering window temperature materials. However, this can be partially overcame increasing the part bed temperature, which reduces the curling effect but increases the solid state sintering of the supporting powder, building up the so called "caking" effect, reducing the recyclability of the powder and hindering the break out of parts.

An important feature for SLS users is the surface quality of the sintered parts. The base reference is the quality obtained by other competing technologies like injection molding (IM). However, a direct comparison is not appropriate, because during the IM process the use of a metal mold and injection pressure allow that the physical polymer boundaries match almost perfectly the internal mold surface cavity. In case of the laser sintering process, the part boundaries are constituted by powder particles. Therefore a polished and perfectly defined surface is not achievable, presenting a particular porous structure defined by the particular powder size distribution and polymer rheology.
In Figure 20 the surface roughness results are depicted. These measurements were performed by a tactile system over the surface of a benchmark part (water filter cap), considering the characterization parameters Ra and Rz.



Along the X direction (sintering plane direction), the results for both Ra and Rz using the Step Up material are lower than the benchmark or reference powder Durafom PA. Nevertheless, when the Z direction is taken into account (perpendicular to sintering plane direction), no roughens improvement can be observed, even presenting an important difference between both materials. However, this partial achievement is particularly important, because it shows that a better surface quality can be obtained even for materials with a higher apparent viscosity. Thus, this improvement increases customer acceptance and nears results towards injection molding.

The industrial laser sintering trials for **consumer goods** were performed at +90 facilities.
No delamination was observed between sintered layers. It was not possible to deform parts plastically. After some elastic deformation, the parts broke without any sign of plastic deformation but the breakages were across the layers which also indicated that the layers were sintered correctly and there was no delamination. The parts were scanned with a laser scanner (comparable system as BMW uses) and compared with the CAD data. Apart from one measurement point with a gap distance of 0.45 mm, the average deviation from the CAD data was around 0.1 – 0.2 mm. The results may be improved by re-calculating the shrinkage in all directions based on these measurements and scaling the part for

compensation. In adjusting the parameters that way the parts fulfill the requirements of the actual product.
The parts looked more porous and rough than those built whith PA2200 polyamide material.

Two layers of 3+1 acrylic primer were applied to see if it is possible to increase surface quality and appearance using standard post processing. Then, surfaces were sanded to a smooth finish using 220 grit (dry) and 500 grit (wet) sandpaper. Unlike the PA2200 material, the surface was very smooth, free of pinholes or other defects and ready to be painted.

Impact

The impact of STEPUP project is the removal of technical barriers for opening the way for wide-scale introduction of rapid manufacturing products and technologies in a wide range of sectors. Current limitations that the project is aiming to overtake are represented by:
a) Material Properties; b) Material Costs; c) Material Durability – Life; d) Surface finish; e) Process Repeatability; f) Speed and Cost of systems g) Designer Mindset – “Design for Manufacturing” needs to be “Manufacturing for Design”.
Three demonstrative sectors, automotive, consumer goods and instrumentation applications, have been chosen to demonstrate the possibility of substitute and replace conventional products and manufacturing techniques.
In this way it will be possible to realize 3D objects which will allow to perform:

- Functional Testing with mechanical properties close to Injection Moulding Plastics
- Small series for customer cars and their equipment
- End-products for consumer goods and medical instrumentation fields

The analysis indicates that the main important technical objectives that will allow to have the expected impact (replacement of conventional products and technologies for a wide range of applications) are:

- Achieving the material properties and the proper durability of parts
- Improving process repeatability;
- Improving product customisation and personalization (especially for consumer goods applications).
- Reduction of time-to-market for parts supplying and small series manufacturing to 1 day (vehicular applications).
- Fast repair and maintenance service;
- Reduction of stocks (all applications)
- Possibility of realize very complicated shapes

Economical impact

A very important aspect to consider for a positive exploitation of the project, is the **costs compatibility of the process proposed**, with the manufacturing costs that are acceptable by the market.

For these reasons, STEPUP strategy foresees the development of cheaper SLS polymers having better and customized performances, through the introduction of an innovative and cost competitive technology (the mechano-chemical approach).
The project impact, considering the necessity of the different needs of the companies involved in STEPUP, can be defined under qualitative terms as follow:

- Improve **the range of raw materials manufactured** (MBN)
- **Increase company turnover** and number of people employed (MBN, +90)
- Increase the **competitive advantage**, thanks to the customisation and innovation of products (+90, SMEs orbiting close to INSPIRE)
- **Cost reduction** of vehicular components (BMW).

The selection of viable process conditions and post processing treatments has always kept into consideration the economic aspect of the materials and application.

Targeted market

The market for additive manufacturing in 2010, consisting of all products and services worldwide, grew 24.1% (CAGR) to $1.325 billion, up from $1.068 billion the year before. The industry declined 9.7% in 2009, but grew by 3.7% in 2008 and 16% in 2007
The $1.325 billion estimate is comprised of revenues generated in the primary AM market. This market consists of all products and services directly associated with AM processes worldwide. Products include AM systems, system upgrades, materials, and aftermarket products, such as third-party software and lasers.
The revenues created by these products and services are considerable, but not large compared to many other industries, or even some companies. However, it is important to also consider the overall economic impact that the technology is having on countless design and manufacturing organizations worldwide. For example, Graco Children's Products is producing 6,000–8,000 parts per year—all with four AM systems and one person.
The additive manufacturing industry is expected to continue its double-digit growth over the next several years. By 2016, Wohlers Associates believes that the sale of AM products and services will exceed $3 billion worldwide, as shown in the following chart. By 2020, the industry is expected to surpass the $5 billion mark. The numbers in the vertical axis are in millions of dollars
An estimated $265.9 million was spent on materials for all AM systems worldwide in 2010.
This is an increase of 22.1% over the $217.8 million spent the year before. The market segment declined 8.5% in 2009 and grew by 7.7% in 2008. These estimates include liquid resins, powders, filaments, sheet materials, and all other material types used for additive manufacturing. The following graph provides a 10-year history of material sales for AM systems worldwide. The figures shown are in millions of dollars.
In relation to the SLS technology, the worldwide market for laser-sintered polymers is believed to be an estimated $83 million in 2010, according to Tim Gornet of the University of Louisville. About $53 million of this total are sales outside the U.S. Gornet estimates the worldwide LS material consumption to be about 900,000 kg for the year. The worldwide total is up from about $62 million in 2009 when consumption was an estimated 775,000 kg for the year.

Materials Properties Comparison

Currently, the SLS materials market is dominated by polyamide based matrices. According to Table 1, which summarizes more than 80% of the material types commercially available, more than 50% of these materials are based on polyamide. As observed, the companies EOS and 3DSystems share more than 90% of the whole market with products that are pure PA12 or composites that are PA12 based. Other minor companies, such as CRP Technologies, also offer other composite products, like carbon fiber mixtures, but their polymer matrix is also PA12.
One possible explanation of why the PA12 matrix dominates the market is its ease of processing and the convincing sintering results coupled with its mechanical properties. These three characteristics are

fundamental to consumers, which are mostly service bureaus and internal company research or design divisions. They select and purchase materials according, of course, to their particular technical demands, but mainly to allow them to reduce design cycles and release products faster into the market, with materials that present a higher confidence on its reproducibility results and ease of handling. Of course that PA12 presents its limitations and the customers complain about the higher material purchase costs and claim for further improvements, particularly in relation to mechanical properties and surface quality (roughness).
But the transition to other “unknown” materials represents also a high risk in terms of cost and adaptation times. A clear example is the introduction of Orgasol Smooth from the company Arkema. This material presents a lower refresh rate in comparison to PA12 from EOS or 3DSystems and a similar purchase price, which represents a direct cost reduction and therefore a competitive material. But the processing is more difficult for operators with lower experience, which represents for the moment a higher entrance barrier into the market. However, the continuous improvement of SLS equipment, particularly in relation to their temperature management, will in the near future allow a higher acceptance and will transfer the sintering processing success and results to the machine capabilities and confidence, and not left them just to the operator’s skills.

In relation to the Step Up project outcomes, the most promising material developed to date is based on PA12 compounded with nano platelet using the novel High Energy Balling Milling Technique (HEBM) and post processing step. The initial selection of a PA12 matrix is based mostly on a commercial strategy. The main idea behind was not to develop a completely new product to avoid that customers may be reticent to adapt it at their facilities, but to take the most common commercially available material and improve its characteristics by incorporation this new nano-phase. Among these characteristics, two main aims were considered: first the improvement of the mechanical properties and second the reduction of the refresh rate. In relation to the mechanical behaviour, as an example, Figure 5 depicts the results for the Dynamic Mechanical Analysis of a sintered part employing the PA12 from 3DSystems and the new developed material. These curves represent the elastic behaviour of both materials in relation to the temperature in a range between 20ºC and 180ºC. As noted, below the glass transition point, 3DSystems PA12 presents a higher value in comparison to Step Up PA12, but this difference continuously reduces as the temperature increases.
Indeed, above 60ºC approximately, both curves crosses and Step Up PA12 presents a higher resistance until the melting point is reached. Normally, the operating range for polymers is set below the glass point to avoid the considerable reduction of the stiffness. However, many commercial applications request that materials can adequately resist up to 100ºC and this new material offers to customers an improved solution to their claims while maintaining basically the same polymer matrix. Besides the previously mentioned advantage, other important factors are also the ease of processing and the reduction of the refresh rate. In relation to the first aspect, the new material developed still demands certain experience from the SLS operator due to its reduced sintering window. However, this factor due to its qualitative nature, results difficult to evaluate and a market acceptance forecast cannot be predicted. Nevertheless, the improvement of the refresh rate with a ratio below 30% makes this novel material to offer improved advantages in comparison to the actual market competitors

Cost evaluation

Even if the new invented material shows improved performance, the powder should be price competitive to existing SLS powders, which are available in the market. Until now, there are only a few raw material supplier for SLS powder, what results in an almost monopoly position for them.
The cost of the process is divided into three sections:

- Pre-process costs: Due to good flowability and powder size distribution, the costs for raw materials could be lower than normal, but, due to cryogenic grinding, that increase costs, we can affirm that the costs are similar with conventional ones;
- Process costs: several factors should be considered:
    - The laser power: similar to conventional process;

  - The different temperatures in the machine: similar to conventional process;
  - The possible building volume: similar to conventional process;
  - The time for heating up and stabilizing the temperature: similar to conventional process;
  - The time for cooling down: similar to conventional process or less;
  - Layer delay time: similar to conventional process;
  - The filling degree of the machine: similar to conventional process;
  - Costs for additional adjustments at the machine: No adjustments required to use the new invented powders;
  - The recycling rate: similar to conventional process;
- Post process costs: the behavior of trials was very good and the efforts were as expected. All parts didn't show obvious tendency to shrink or warp more than usual, indicating that no additional work to produce parts with adequate accuracy was needed. In previous chapter, it was shown, that +90 manufactured some parts and improved the surface quality by finishing and painting. The results were very good and it was seen, that this is also possible with normal processes and no extra costs compared to other SLS parts;

To summarize, the process costs of the StepUp material are comparable to the most successful SLS materials like PA 12 from EOS or 3D systems.
As the process costs of the StepUp material are similar to the current SLS powders, we need to have a look at the material costs. On the market there are several other materials available.
The costs for the most common materials of PA 12 (Duraform PA and PA 2200) are between 60-70 €/kg. The materials from Arkema are a little bit cheaper, but the recycling rate is lower. Therefore, the overall costs are not lower for these powders.
The surface quality and toughness of Sinterplast PP from Microfol is not very good. For that reason, it cannot be used for all applications.
Materials with a different property profile like Duraform Flex with higher elongation at yield or even PEEK with higher heat distortion temperature and better flame retardancy have even much higher prices.

The StepUp powder was analyzed by MBN and Matres regarding their cost structure. There was a detailed view at the process for producing the powder. Then, several calculations were performed to estimate the potential costs for an upscale of the existing machine equipment.
To sum up, the price for the StepUp powder will approximately be 37 €/kg. This is a full cost analysis and includes all costs for the raw materials, gases, electricity, investment costs, packaging and logistics.

This price is cost competitive to materials currently available in the market.
To summarize, even if the economic analysis of the process cannot be finalised, as it was not possible to determine the recycling costs due to the shortage of the material, the price for the StepUp material looks very promising.
The material impact can be very high, if the results of the recycling rate are as expected and the final part properties can be verified with different material lots on different machines. This will result in a replacement of existing materials. As the price of the material is the most important hurdle for further impact of additive manufacturing. This development could result in an increase of applications in the worldwide market of additive manufacturing, as the price is decreased compared to currently available materials. A quantification of this market penetration cannot be done as long as the details mentioned above are not clarified.
The production protocols of SLS automotive, medical instrumentation and consumer goods applications as well as an eco-evaluation of the process and materials impact are described.
To summarize, some facts can mentioned:

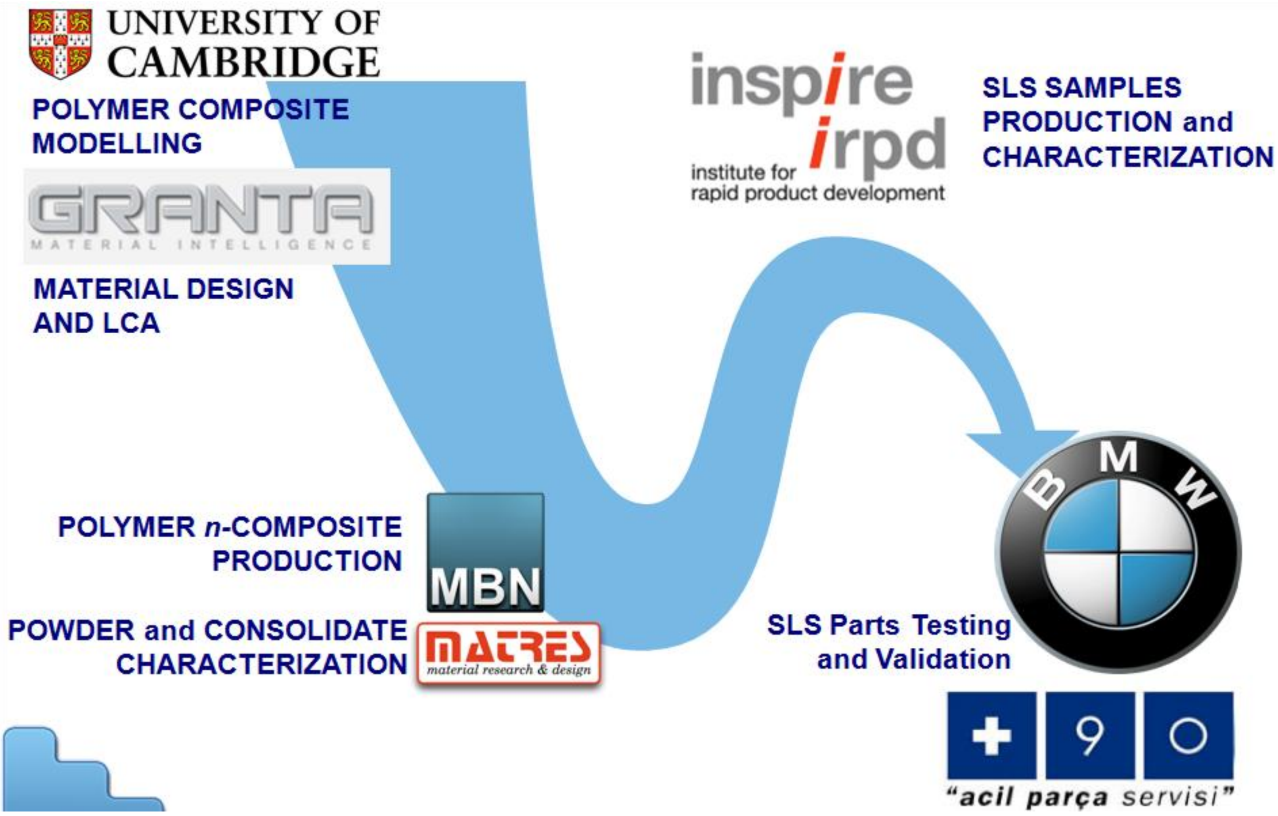
- The powder was analysed by nano CT and the results were implemented in the roundinging process;
- The powder flowability was analysed (PP, PA 12L, PA 12/3% platelet) and it was found, that it has an outstanding flowability;
- PA 12L was processed, but needs to be improved in terms of the process window;
- PA 12/3% platelet was processed successfully;
- The mechanical property were similar to commercial materials;
- The accuracy covers the requirements;
- The benchmark parts were produced successfully;
- The process costs are identical to the commercial process;
- The material costs look very promising, but depend strongly on the recycling rate, which has to be evaluated.

The industrialization has not been finished yet, but based on the results so far, a successful market penetration is realistic.

Consortium

The consortium working approach makes sure that all partners can contribute to the project from their strengths (and in consequence improve their knowledge and their places in the European RM market); implement effective, efficient, and focused European research; develop demonstrators and commercial prospects related to Selective Laser Sintering (*SLS*) nanosystems and RM technologies.
The Consortium has been built around a clear concept of a manufacturing chain capable of achieving the project objectives. The STEPUP consortium was convened in order to bring successful RM innovation to the automotive, instrumentation and consumer goods sectors.

From this description it is clear that the STEPUP consortium has "inside players" capable of disseminating knowledge acquired in the project at high scientific and technological level, and has the right tools to exploit the result achieved in the market.



STEPUP Consortium Partners and their main roles

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