Executive Summary:

CompoLight addressed the problems related to the implementation of Rapid Manufacturing (RM) as a competitive production technology for the European industry. The project solved identified shortcomings of RM related to design and production of lightweight metal parts. The lack of design rules for RM, which could guide the designer, the lack of guidelines and simulation software to support to the user in the work preparation prior to RM processing and predict quality features and mechanical properties of the part are some of the deficiencies.

CompoLight is, by means of experiments, applied research and software development; centred on the 3 archetypes of lightweight metal products. These products are respectively

1. Parts with complex internal channels/cavities to provide thermal optimization, mechanical or hydraulic functions, lubrication, i.e. the internal structure is geometrically defined but not repeating - channels/holes

2. Parts with internal structures or hollow zones to reduce the weight, i.e. the internal structure is geometrically defined and repeating (uniformly distributed) - honeycombs

3. Parts with porous internal structures to be used in air or water filtering, fluid flow control, noise reduction or specific tool components. The internal structure is geometrically undefined and statistically distributed porosities.

For example, one of the most important impacts of the project is related to the environmental aspects. The weight reduction demonstrated and obtained during the project proved that the implementation of the technology in transport sectors could have a significant impact on the fuel consumption.

The CompoLight project demonstrated that the weight reductions on hydraulics blocks were between 70% and 95%. The weight reduction is not only relevant for the fuel driven vehicles. All Electrical cars need weight optimisation to improve the travelling distance with a fully charged battery. In the same way, the reduction of material consumption is contributing to a better use of our natural resources. Furthermore, the technology is only using the absolute necessary material in contrast to material removal technologies.

Energy losses in hydraulic components and other flow systems have also been reduced due to geometry optimisation of channels and cavities. The pressure loss through the hydraulic blocs went down with 93%, reducing the in service energy consumption. This is very promising, since more than 10% of the world's energy consumption relates to pump systems. It also nicely supplements the on-going effort in legislation-driven reduction of energy consumption that Europe has witnessed with unprecedented success in recent years.

Technology is still important for the European industry and rapid manufacturing offer the ability to com-pete on functionality and not only on price. New knowledge optimised products give higher competitive advantages and as the rapid manufacturing technology is quite flexible and does not need much manual work, it will help preserve European industry workplaces.

Furthermore, Compolight contributed on the ISO standardisation of the AM technology, and the general European research by showing new path for the AM technology.

Please see the website http://compolight.dti.dk for further information.

Project Context and Objectives:

CompoLight should solve identified shortcomings of Rapid Manufacturing (RM) by addressing five areas, all of which are related to design and production of lightweight metal parts. These deficiencies are:

1. lack of design rules for RM, which could guide the designer,
2. lack of guidelines and simulation software to support to the user in the work preparation prior to RM processing and predict quality features and mechanical properties of the part,
3. CAD application software to augment - partly automate - the design of internal structures of a part,
4. research in the effective use of RM integrated in a process chain jointly with conventional processes, and
5. lack of ways to define and effectively control surface qualities.

CompoLight is addressing these problems by means of experiments, applied research and software development. The work is centred on 3 archetypes of lightweight metal products, all of which are parts with internal structures, respectively

1. Parts with complex internal channels/cavities to provide thermal optimization, mechanical or hydraulic functions, lubrication, i.e. the internal structure is geometrically defined but not repeating - channels/holes
2. Parts with internal structures or hollow zones to reduce the weight, i.e. the internal structure is geometrically defined and repeating (uniformly distributed) - honeycombs
3. Parts with porous internal structures to be used in air or water filtering, fluid flow control, noise reduction or specific tool components. The internal structure is geometrically undefined and statistically distributed porosities.

The consortium comprises 12 beneficiaries from six EU member states: 4 RTD, 6 end user SMEs, 1 SME provider, and 1 large industrial company. Projected impact from the project originates from a larger industrial utilization of lightweight components in many industries, including automotive, aerospace, medical and electronics. For each of the participating SMEs, the opportunity to strengthen their market position is the crucial argument for taking part in the project. Societal impact is exemplified in terms of potential reduction of CO2 emission from cars and equivalent savings in fuel consumption. Dissemination of project results involves all beneficiaries in activities ranging from demonstration events in each of the participating companies via RM cluster building, seminars and exhibitions to special training courses and the integration of RM curriculum in university studies.

Overall strategy and general description:

A set of technological problems have been identified, each of which forms an obstacle for a wider exploitation of the undisputed advantages of RM: the potential to manufacture complex parts with a high content of technology in small batches or single piece production. Each of these problems represents themes, which have emerged in discussions between project beneficiaries. Main emphasis in these discussions has been on the requirements met by the SMEs in the daily work for their clients. In order to secure that project results can be implemented and satisfy the need of the industry sector for which they are developed, we have chosen the following strategy in the design of the project:

Project RTD work is broken down in five technical WPs, one WP on Dissemination and Implementation, one on Demonstration and one on Management. In the following section a short overview of the WPs is presented, whilst details of the work are presented in tables on the following pages.

Work Package no. 1, Product definition and design

The main objective of this WP is to develop a set of design rules, serving multiple purposes. One purpose is to analyse a metal part or a technological problem with a view to assess whether it is suited for Rapid Manufacturing, and in case of yes - what process should be selected and what process parameters are most likely to provide with a good result. A second purpose is to provide the product designer with a tool, which he/she can use to adjust the geometry and the selection of material and other properties of his/her design to fit - as far as possible - to the special opportunities and limitations of RM. The output of this Work Package is a set of guidelines, supported by software to optimise the processing of a metal part by RM and ensure that the part is produced in a way that it fulfils the requirements of the customer. These guidelines assist in the selection of the best possible RM solution as well as optimal process parameters for the process selected. Special attention was given to information to the RM operator about support structures and other practicalities.

Work Package no. 2, Simulation

Data collected by CompoLight beneficiaries shows that the average scrap rate for geometrically complex parts is more than 30 %. The target is to bring this down below 5 %. For simple parts, the figure will be close to zero. The problem is that the number of process parameters, which can vary, is virtually unlimited, as they include traverse speed, layer thickness, powder composition and grain size, distance between pulses, laser power and refresh rate and many others, depending on the type of machinery. So, it is crucial that types of similar problems (material/geometry/surface requirement/size, etc.) are grouped together and "first time right data" recorded in a structure, which allows the user to benefit from them subsequently.

The objective of this Work Package is to develop an application software packet to optimise the processing of a metal part by RM and ensure that parts are produced in a way that they fulfil the requirements of the customer. Specifically, this means that research work will focus on simulation of the RM process in order to have a "first time right" selection of all process parameters. In addition, a number of materials will be tested and their RM - related properties found and quantified in a way that makes them suited for use as input parameters in a standard, commercially available simulation software package. The aim of this is, of course, to optimise the products to their limits and to build a basis for the exploitation of a variety of composites. This is particularly relevant here, because the RM processes - together with various sintering concepts - offer almost unlimited opportunities for optimized material selection.

Work Package no. 3, Manufacture

The objective of WP 3 is to develop, document and demonstrate methodologies that enables standard RM systems to be used in industrial production of a selected set of products. Using tools developed and experiences gained in previous work packages, components of the project focus will be produced on RM systems, which must be adapted or reconfigured to handle the different types of internal structures. Parameters to be taken into account include materials (powder, composites, and infiltrants) and processing (process parameters, printing strategies and support strategies). Together with WPs 1 and 2 this WP will result in better a quality of finished parts, reduced scrap rate and a shorter lead time. The Work Package is divided in six major sub-WPs, each of which takes the project one step closer to these objectives:

1. Validation toolbox. RM technologies have many different capabilities to produce complex geometries: support structures required or not, accuracy, surface quality, internal structures complexity limitation, porosity ability, excess powder removal, material properties, building speed, maximum dimensions, availability of internal file format for the layers,

2. Rules for lightweight parts. Lightweight internal structures are typically complex geometries impossible to produce with conventional techniques like CNC. RM processes bring efficient solutions to build such complex parts but several problems still have to be overcome. The size of the file becomes huge and may drastically slow down the building process. The removal of excess powder is also an important issue.

3. Rules for parts with internal channels. Parts with internal channels are also very difficult or impos-sible to build with conventional techniques, especially if the channels are long and tortuous, which is the case for complex hydraulics components. The size of the file may be huge only in the case of numerous and long channels. The removal of excess powder is here a very important issue and shows fully different situations with direct and indirect RM techniques.

4. Rules for porous parts. Porous parts are typically complex geometries produced by the RM process itself and not only by the 3D CAD file. A combination of process porosity and additional holes is possible with the purpose of enlarging the range of void zones in filters or to producing graded porosity using local variations.

5. Infiltration and sintering. Post machining is clearly required with near net shape manufacturing techniques but this will be performed in WP5. The steps involved here are only infiltration and post sintering required to enhance mechanical and thermal properties.

6. Process quality. Currently, the metal RM processes become mature enough to produce accurate parts with complex details and good mechanical and thermal properties. But are they able so far to produce short series of metal parts with a satisfactory reliability and stability? The WP will define some quality management tools for this matter.

Work Package no. 4, Data handling

The objective of this WP is to develop new concepts and software tools to improve the design and handling of complex parts with different types of internal structures (e.g. channels/holes, honeycombs, pores). The design of internal structures with present CAD systems is very complicated and time-consuming especially for complex parts with small structure sizes. The ability to manipulate the interior part volume adds a completely new dimension to design systems, which results in very large and often not manageable file sizes. Separate software modules for the generation of input to the RM systems will be developed according to the product definitions of WP1 (see picture, MB Proto).

1. Efficient techniques and interfaces for an improved data handling of structured parts allowing to process and prepare very large CAD files.
2. Software for the automated design and generation of complex lightweight structures with a structure size < 100um.
3. Automated design and handling of internal structures for porous parts.

For parts requiring internal structures, analyses by project beneficiaries indicate that time for generating the necessary data for the RM machine will be reduced by more than 75 % in average. For complicated parts this could mean from 5 days to one.

Work Package no. 5, Surface Quality

The objective of this WP is to develop strategies and technologies to finish the part according to the end-user requirements. Generally, all current "rapid technologies" suffer from poor surface quality and need post treatment in order to meet the geometric or cosmetic requirements. Disadvantages of this include high costs and uncontrolled end quality. All this has to be avoided especially when moving from Rapid Prototyping to Rapid Manufacturing, which is aiming at producing series of parts. The following will be developed for specifically the geometric requirements:

1. Efficient and automated strategies to remove support and overhanging structures.
2. Surface texturing, camouflaging the typical stair-stepping; adding new surface geometry, cosmetic as well as functional (e.g. a larger cooling surface can be achieved in channels), see picture.
3. Automatic post machining: machining data will be retrieved from the CAD file about surfaces, for which dimensional accuracy or surface roughness require post machining
4. Mechanical and chemical ways to finish internal channels and (porous) structures.

Work Package no. 6, Dissemination and Exploitation

The main purpose of dissemination and exploitation is to secure that project results are disseminated to all parties which may have a scientific, technical or commercial interest in them, and that exploitable results are adopted and implemented by existing and potential users - first of all, of course by the industry beneficiaries themselves. In this way, CompoLight will contribute to the development of new RM technologies and the augmenting of existing ones by making generally available experiences gained in the project.

Exploitation policy: The project will generate new knowledge, which is immediately implemented by the consortium members, giving them a competitive advantage, which they will exploit right ahead in their day-to-day commercial activities. The External Industry Interest Groups make up an important target group for exploitation. Many vendors of RM technology, and developers of simulation software and materials participate in these groups, and they are invited to implement the results from CompoLight in their standard product, according to agreement with IPR owners in the consortium.

Project Results:

WP1 Product definition and design

Task 1.1 Concepts, requirements and limitations of structures for RM applications

A wide overview of concepts, requirements and limitations of structures for RM applications has been reached and presented in a report. The gathered information concerns a range of manufacturing machines and serves as a basis for the developed design rules and process recommendations of T1.2 and T1.3. The work has focused on standard materials for each machine, but other materials has been tested as well (aluminium, titanium, copper).

Task 1.2 Definition of design rules for internal structures to be made by RM

For an efficient use of models and prototypes during the different steps of product design, it is necessary to have a wide knowledge of the additive manufacturing processes and their properties. Only in this way it is possible to obtain the maximum of their capabilities. Every process offers its own advantages, making necessary the optimization of the models to be built. For this optimization experience and know-how are needed, making the design of adequate models in many cases a difficult mission. Frequently designers and users disapprove the application of additive technologies, because the design phase becomes an obstacle due to a lack of information regarding design rules. Many work groups are making some efforts in this field of guidance. The purpose of this task is to offer detailed information for designers working with metal manufacturing systems such as Selective Laser Melting (SLM) and 3D-Printing.

Design for manufacturing and assembly (DFMA) can be defined as the practice of designing products to reduce, and hopefully minimize, manufacturing and assembly difficulties and costs' [1]. This sentence is 100 % applicable to well established manufacturing processes (casting, milling, drilling, forging, extrusion etc.) where the designers need to understand the constraints imposed by the processes. The extensive effort on design for manufacturing and assembly over many years indicates the difficulty and complexity surrounding this topic. AM technologies do also have constraints, but the potential of AM systems lies exactly on this issue, the oblivion of many constraints as a result of a toolless manufacture.

Analogous to the basic principles of shape design where it is necessary to describe the elements which can be formed, this task defines the features and geometries which can be difficult to build with AM technologies. The catalogue of design rules shall assist the designer in understanding the design freedom, while giving some restrictions based on each process and machine. Here are some elements, which can be taken as the base for many other forms.

For the analysis of many of these features a benchmark was used. Using it, measurements of the features are easier to perform. The benchmark part represents a particular test part. The proposed benchmark was thought to reveal a wealth of properties. The results of the measurements should be understood as a demonstration of the forms that are possible to build without risk. Some of the small features are possible to build, but represent a high risk due to the influence of many machine parameters and their variations.

The benchmark part dimensions are 50 x 50 x 5 mm^3 and it has altogether 14 groups of features. The majority of the measurements were done with an optical microscope and evaluated with appropriate software. Most of the features were evaluated in x- and y-direction trying to exclude the influence of the re-coater, which is moving in x-direction with the re-coater blade parallel to the y-axis contrary to the direction of the x-axis.

Task 1.3 Definition of process recommendations for internal structures to be made by RM

Not all geometrical features are suitable for every RM process and vice versa. RM processes differ in certain details of processing and some are more applicable for determined complex geometries than others. This is especially important when producing hollow structures and cavities as well as with all kinds of support structures. Based on the results of T 3.1 and on the general state-of-the-art, an analysis of RM processes concerning building possibilities and restrictions have been made and a list of recommendations for the process to choose for a specific feature of internal design has been gathered and presented in D1.3.

Task 1.4 Automated inspections of geometries regarding RM producible internal structures

Based on the results from the other tasks, a set of functions to analyse both complete components as well as unit cells of complex lattice structures have been developed and implemented in the Marcam AutoFab software. For complete components, the software currently detects:

1. Undercuts
2. Surface areas parallel to the building platform
3. Surface areas positioned under specific angles
4. Surface areas having specific wall thicknesses

For unit cells of complex lattice structures, the software detects:

1. Stability issues, e.g. are the cell connected
2. Symmetry issues, e.g. are the connections symmetric
3. Processing time issues, e.g. expected processing time and number of triangles

WP2 Simulation

Task 2.1 Process simulation

The use of the Finite Element Method (FEM) in product development is now well established. However, its use in manufacturing processes is not very common and is part of the field of new applications in computational mechanics. The most important reason for this development is the industrial need to improve productivity and quality of products and to have a better understanding of the influence of different process parameters. The importance of the numerical simulations lies in determining the evolution of stresses and deformations to predict, for example, susceptibility to cracking and thus to prevent failures during manufacturing or even service.

The primary aim of these process simulations is to predict the distribution of residual stresses in a SLM product and determine the influence of the variable process parameters on these stresses. For instance, the influence of different types of support should be studied. Thus, the simulation software can become an extremely useful tool when designing and dimensioning both product and the necessary support. This should significantly reduce the interval between the first idea and finished product and improve the 'first time right' rate.

After a survey of the different multi-physics software solutions, OOFELIE::Multiphysics from 'Open Engineering' was chosen as the platform on which the simulation should be build. OOFELIE::Multiphysics includes moving heat sources, steel metallurgy, temperature-dependent material properties, elastoplasticity, non-steady state heat transfer and mechanical analysis.

Two simulation approaches have been studied within the CompoLight project. The first one calculates microscopic physical phenomena that appear during the laser scanning of the powder bed. The second one estimates the thermo-mechanical state of the parts during and after the SLM process. Each approach has its advantages and its drawbacks.

SLM machine users could use microscopic analyses to help in the setting of the laser scanning strategy. They would also need numerical studies at a macroscopic scale to estimate the best way to conceive and position the supporting structures during the process. Numerical simulations can decrease the number of machine crashes, due to the excessive thermo-mechanical deformations, by preventing it.

Producers of SLM parts could also be interested by macroscopic analyses, to prove to their customers the quality of their products. Moreover, it is comfortable to know, before building a part, information about its mechanical state at the end of the process, and to be sure that the final deformations fit with the specifications.

Limitations in the State-Of-The-Art simulation technologies have been identified. They come from the huge gap between the scale of one layer (order of the microns) and the scale of an entire part (order of the centimeter). Several ideas have been proposed to solve these limitations. One of them is to join the advantages of both micro and macro scale analyses into multi-scale analyses.

Task 2.2 Quantification of materials and processes

CompoLight has significantly contributed to the on-going work on examining and characterizing porous parts made by specific sets of process parameters. The overall goal is to be able to link process parameters with final part properties. This will allow such materials to be used in simulations. In this lies an aim of being able to produce porous parts where the degree of porosity and other porosity characteristics such as pore sizes are fully controlled by the machine operator. Extensive work has been made on characterizing how porosity varies with key process parameters such as laser power and hatch distance. Results can be found in the D2.2.

Extensive effort has been made to find out whether the RM metal technologies can produce porous parts that resemble sintered parts to some extent. As a first step DTI tried using powder from traditional sinter-ing technology in the MTT SLM machine, but material properties turned out quite different from traditionally sintered parts (much harder and with bigger pores). Several attempts on revealing the pore characteristics of two filter parts by normal cutting and also by femtosecond laser cutting have been made, but none of these have had a successful outcome at the moment. We do know, however, that the pores produced in the SLM processes are much larger than those by traditional sintering. This has indicated that a whole new strategy should be used for producing those materials. Therefore a hybrid technology for porous part manufacturing which combines the SLM and the traditional sintering process has been tested. Loose 316L metal powder is trapped within a hollow SLM produced part, and subsequently heated in a sintering oven at 1250 degrees Celsius. Currently, the porosity is too high, since the powder is not compressed as in traditional sintering. This may be improved by varying the powder particle size distribution. There are also challenges regarding cracks occurring during the heating-cooling cycle and a small, but important, shrinkage of the powder volume, i.e. the final part includes a small void.

One of the big challenges the RM technologies faces are the current lack of standards. To fill in this gap while waiting for these standards we have compared RM metals with traditionally fabricated metals as e.g. material anisotropy due to the building direction will be present. Information on the properties on parts produced by traditional technologies has been collected and compared with properties from the different RM metal technologies in D2.2.

Work has been initiated on which material properties that should be determined for each RM metal pro-cess both in terms of the process simulations as well as further engineering simulations with RM fabricated parts. This has been done in collaboration with Open Engineering and the metallurgical department at DTI. The effect of all the process parameters and the environment has to be taken into account as well as the anisotropy in the build direction.

Task 2.3 Implementation of the parameters in the commercials software

The assembling of a unified material database for each of the processes involved in CompoLight turned out to be harder than expected and several challenges where uncovered during the project:

1. Reproducibility over time on one machine and between identical machines: It quickly became ap-parent, that Rapid Manufacturing of metal is a young and partly immature technology. Several machines in the project was first or second generation and still suffered from unstable operation and varying production results. Secondary operation parameters like air flow within the chamber, variations in particle size distribution etc. turned out to have non-negligible influence on the end result. Thus, when the project was initialized, in some cases you couldn't even manufacture a part with parameters from an identical machine. During the project, these challenges have been solved by introducing procedures for machine operation and maintenance and developing more stable production parameters. However, fully reproducible production across time and machines are still unavailable and requires further development of both machines and supporting technology such as inline monitoring and feedback.

2. Materials data depend on part geometry: Traditionally, materials data can to a large extend be made independent of part geometry. However, with rapid manufacturing of metal, the final material properties are closely intervened with the geometry of the part due to production process itself. Because of the big difference in heat conductance of the solid part and the loose powder, micro-welding a volume of powder with a constant laser power have a strong dependence on the surroundings. Close to the part surface, heat conductance is much lower leading to more energy absorption in the micro-welding volume and thus different final material properties. To achieve a given material properties you therefore need to adjust the

laser power according to the distance to surfaces, or as an approximation, develop sets of parameters for different classes of parts, e.g. large part parameters, small part parameters. Unfortunately, current systems don't allow varying laser power throughout a part, but requires the laser power to be constant. To sum up, even if you measure for example pull strength according to an ISO standard pull sample test species, the result is in principle only valid for geometries with approximately the same cross section as the pull sample.

3. Random porosities leads to large variations in measurements: Even if we neglect the above challenges, measuring a material property of porous parts are difficult: Due the stochastic nature of most of the porous samples in this report, the strength measurements have large variations. If just a few porosities lines up in an unfavorable position, the strength of the pull sample falls drastically. Every single pore can also serve as an initiator for crack formation. In other words, even if you manufacture to in average identical porous pull samples, the strength measurements will probably be very different, complicating the task of assembling a material property database.

4. The material parameters has also been used to optimized the flow circulation in the hydraulics parts, considering the deviation of surfaces, and roughness of the parts produce with the different technologies

Despite these challenges, material properties of close to solid rapid manufactured parts have been meas-ured and a much better understanding of production transfer between machines have been developed. It is now feasible to move production between machines (and companies), and with further development of the machines we expect even better results in the future. The gathered parameters have been distributed to interested companies.

WP3 Manufacture

Task 3.1 Validation toolbox

Rapid Manufacturing technologies have very different requirements and capabilities: Are support structures required or not, accuracy, surface quality, internal structure limitations, porosity ability, excess powder removal, material properties, building speed, maximum size, availability of internal file format for the layers etc. This is the reason why we need to compile a state-of-the-art Toolbox. We also have to define the content of the Toolbox in accordance with the requirements of the case studies from the SME's partners.

The validation Toolbox collects the process parameters and their limitations for each technology in the consortium (DMLS from EOS, SLM from MTT and 3DP from Ex-One/Prometal RCT). It assists in evaluating the feasibility to build the case studies suggested by the SME's. In agreement with all CompoLight partners, this toolbox was completed according to the continuous improvement of various Rapid Manufacturing processes.

Task 3.2 Building rules for lightweight parts

The problem of weight reduction can in general be approached from two complementary angles: material density and geometry. These two concepts merge in the term 'cellular materials', where a microscopic geometric structure is engineered to result in certain macroscopic properties, e.g. density and strength. CompoLight has contributed to several different possibilities.

An obvious strategy to achieve lightweight parts is to use lightweight materials like aluminium, titanium etc. Within the consortium a broad range of metals has been available and valuable know-how has been gathered regarding the build parameters and quality of these. However, the density of the part is still limited by the material density.

To overcome the limits of standard alloys, an emerging possibility is to actively engineer new material with tailored material properties. One way to accomplish this is to control the distribution of two materials either regularly or stochastic. In weight saving applications, one material is typically chosen to be void. In this case, a significant amount of material can be removed, while retaining the strength as much as possible. Both stochastically distributed voids and regular cellular structures have been considered.

Porous stainless steel parts can be produced reliably at densities in the range of 70-100% in the SLM ma-chine by varying the process parameters. Due to the powder size (~50 µm) and the laser spot size (~50 µm), the pore size distribution also centers on ~50 µm. It is, however, possible to achieve smaller pore sizes in the SLM process, by two different methods:

1. By using smaller metal powder particles, the pore sizes become smaller (~25 µm) with some ma-chine parameter settings (laser power is most influential).
2. By trapping loose powder inside solid shell structures and subsequently sintering the part in an oven, the pore size distribution is fully determined by the initial powder size distribution.

In weight/strength applications, the pore size distribution is important due the relationship between pore sizes and strength. There is a particle size effect, or rather a pore size effect: Large defects have more impact on mechanical properties than the same volume of smaller defaults, that's why samples with larger pore size have lower mechanical strength. An advantage of the SLM process is the possibility to grade porosity throughout a part. Thus a part can be solid in critical areas and porous in non-critical areas.

In the ProMetal 3D printing process, the porosity is controlled in the subsequent sintering of the green part. At initial stage of sintering, porosity is opened. As sintering progress, pores shrink up to become unstable (90% density) and make the opened porosity and the mean pore size to decrease. At higher density (>90%), porosity is closed. The pore size distribution can be controlled by the initial powder size distribution.

Replacing bulk material with a cellular structure can potentially remove even more material. A huge ad-vantage is the possibility to design the cell structure according to specified needs, e.g. strength, density etc. A great amount experience in building these types of structures has been achieved through CompoLight and processing requirements has been collected in various deliverables.

Finally, a more general approach is that of topology optimization. Here material is moved until it is optimally distributed with respect to predefined load cases. The design process is almost reversed, since the load cases (and FEM calculations) dictates the shape. Topological optimization is a technique use to simplify a piece as much as possible, i.e. remove unnecessary material while still meeting the constraints. This simplification concerns the shape of the piece, its mass and the rigidity to withstand the force applied. However, topology optimization also introduces quite some challenges.

For example, due to the rather low resolution of the FEM mesh the output from the algorithm is not directly suitable for production purposes. Thus a subsequent smoothing operation has to be applied.

Task 3.3 Building rules for parts with internal channels

Internal channels are much easier to build with RM processes than with conventional methods, which are long and expensive for this purpose, and it might be impossible to do it. It makes sense to build channel by RM technology only if they are impossible to build with other methods.

The RM melting technologies requires support during the building. The process will need new creative design strategies (special sections, special parameters, diameter ranges) to avoid any support removal in these unreachable areas. Avoiding support structure and removing excess powder are two real challenges for long and tortuous channels.

The first work which has been performed was the definition of the machine capability to make this specific geometry. The results obtained in the Design catalogue (task 1.1) and in the Handbook (task 3.1) formed the base for the re-design of the case studies. During those tasks, the CompoLight partners tried to push the limitations of the process. Solutions to build channel without support were developed. The first is a machine capability solution and the second is a design solution. Both could be combined in order to get high performance parts. For the study case, the building speed, the size reduction and the height diminution would be present. Some flow performances are also increased.

On the other hand, indirect technique (3DP) requires no support but involves removal of excess powder on green and rather fragile parts. The work plan contained the determination of channel section, geometry, maximum length, minimum and maximum diameter values for each RM technique, as well as innovative solutions for powder removal.

Each of the RM manufacturers spends long time re-designing a part to adapt it to the technology. Experi-ence shows, that RM building rules are still unknown to the majority of industries. The methodology of building internal channels presented in CompoLight provides the basis for design requirements. If these rules are followed by the designers, manufactured dimensions of the parts will drastically decrease. Fur-thermore the parts will be manufactured easily by the owner of RM machines. We were able to reduce cost for each application, not in terms of basic manufacturing, but in terms of performances and of dimensions. For example the (Im)possible Crossing manifold decreased the volume with a factor of ten and the weight with a factor of twenty. This is enough to demonstrate the better economy, both during shipment and during exploitation time.

The most important thing described in this work is the ability of the laser melting and the 3D printing to build internal channels. Each machine manufacturer presented RM technology as the solution to build 'impossible geometries'. In theory, that is true. But, RM solutions also present some limitations. Those have been listed and tested. The dimensions of the tubes, the supports needed and the powder removal have been defined. The simulation work will permit the engineer to predict the behaviour of RM parts. This is also an important topic in order to decrease the cost.

Task 3.4 Building rules for porous parts

CompoLight clearly demonstrates the possibility of controlling the porosity of parts produced with the SLM machine. However, it is more complicated to achieve a given porosity than just tuning for example the laser power. The porosity is influenced by a wealth of parameters, some of them simple, like laser power, scan speed, hatch distance, some of them more complicated like hatch line length and part-size. Especially the part size dependence is problematic. Because of boundary effects, the heat diffusion is quite different for different geometries. In theory this means that a porosity-parameter curve should be measured for each geometry (and scan strategy) one wants to build! In practice, however, it is typically enough to measure these curves for a limited set of geometries (e.g. 1x1cm^2, 2x2cm^2, 4x4cm^2, etc). Another challenge is the influence of the previous layer. Building a porous layer on top of another porous layer requires different parameters compared to a porous layer on top of a solid layer, since voids can propagate upwards.

Changing parameters to obtain a given porosity also influence the part quality. A lower power will often provide a better quality part but will also be more time consuming. Furthermore, a smaller hatch distance (distance between the laser scan tracks) will give a better looking part but at the expense of construction time. So in conclusion it is often a trade-off between time and quality.

Concerning the Prometal process, it is very important that the metal powder has a compatible wettability with the binder to guarantee the cohesion of the metal particles before the oven step. The quality of the recoating step is depending of the powder structure. It is easier when the particles are spherical than non-spherical. The average size particle was 27µm for the SS 316L tested and it was impossible to recoat non spherical particles with about the same size. But it is possible to have a good recoating with non-spherical particles if these particles are finer (1 - 4µm).

To have a good management to obtain controlled porous parts by 3DP Prometal process, it is essential to 'play' with the size of the powder to guarantee the pores size. The management of the thermal cycle will fix the density and the percentage of the open porosity. Behaviour of sintering is specific to the material. For instance, it is depending of the melting point.

The main conclusion is that it is possible to obtain porosity parts with different materials in a wide range of porosity and pores size despite of the requirements. The most difficulty to obtain good results is the shrinkage and warpage management during the sintering step in the oven. The experience of the operator is a critical parameter to guarantee the result.

The results of this task show also a potential for future activities like: other materials (Al for instance), mix of porous and lattice structures and similar applications like the 'Assy' parts. General conclusion is that we have solutions to produce controlled porous parts and a potential to develop other investigated ways in this project.

Task 3.5 Infiltration and sintering

In the beginning of the project, Sirris organized an internal brainstorming resulting in a list of possibilities. Two technologies are available in Sirris: Optoform and 3DPrinting Prometal. Another technology was avail-able in the consortium, the laser melting (EOS and MTT machines from DTI, IFAM and MBProto). Initially, it was evident that Optoform and Prometal were the most appropriate. Indeed, the goal was to obtain light parts with full or near full sintering. Laser melting aluminium was not available in the consortium in this time. Furthermore, TNO has investigated a solution using the Digital Light Processing for production of an innovative design in ceramics (ALN).

The Optoform process has a good potential to produce light ceramic parts and particularly full or near full density parts in alumina, alumina/zirconia or SiC. Unfortunately, initially the Optoform process was not dedicated for the CompoLight project and actually, the two Sirris machines are full dedicated to a medical application.. The preliminary results of the infiltration under pressure were a bit disappointing, but on the other don't give the right idea of the limits of this infiltration process. The used experimental device was not optimally tuned. Ideally, the preheating temperature should be 750°C instead 600°C tested and post pressure should be 25-100 MPa instead 26 MPa. In addition, this process requires a resistant tool and this is a limit concerning the complexity of the geometries. Finally, the used pressure is high and it is possible to have warpages if the infiltration process is not well controlled. The spontaneous capillarity infiltration of alumina by aluminium alloy is possible, but the results are very sensitive to small variations. Moreover, the addition of Mg creates compounds with alumina which weaken the reinforcements. So, we needed to have a compromise able to give a good wet ability and a limitation of the reactions at the interface. This way has been tested only for small thicknesses. The vacuum casting process gives the best results. In this way, it is also possible to manufacture complex geometries.

3D-printing Prometal RXD can work with a lot of different powders: steel (316L, 420, 17-4PH,), nickel, copper, bronze, SiC, aluminium. The only condition is the powder wet ability by the binder. Problems occur most often after the shaping process, during sintering or infiltration.

The Digital Light Processing result looks very promising. With the bare eye the sample looks a little rougher than normal parts produced with DLP. The layers show some inhomogeneous particles in the suspension, probably caused by uncontrolled curing of the material due to x-y scattering. The examination with SEM shows some porosity at the surface. It could be that some ceramic particles are spooled away while cleaning the test parts ultrasonic. This could prove low adhesion between the resin and the ceramic particles. Further SEM examination of the inner structure could prove if this effect occurs only on the surface.

Task 3.6 Process quality

This validation of stability and reliability was performed on samples as well as real CompoLight parts to check the scattering of values such as accuracy and mechanical properties. The project achievement is a handbook of guidelines to guarantee high reliability and stability of the 3 RM processes. The metal RM technologies have matured enough to produce accurate parts with complex details and good mechanical and thermal properties.

A useful tool was developed at the beginning of the project, namely error reporting. It is a survey of the different manufacturing defects and shows which part was manufactured, the date of production and the type of material. This report allowed us to quantify the defects. Then, it helped us to analyse the defects, understand why there was a failure and what was needed to eliminate the defects. Our experience led us to follow and control many machine parameters. For the SLM, DMLS and 3DP we have to control: Powder, start-up procedure, machine parameters like temperature, laser power etc., support strategies, preventive maintenance.

Every few months, one should perform a calibration of the machine and control the laser power. Every production one should check the wiper of the SLM and change it if it is necessary. A damaged wiper affects the quality of the production.

All partners are now having production success rates around 80 % - a big improvement from the success rates of approximately 30 % at the start of the project.

WP4 Data handling

Task 4.1 Data representation and interfaces for the efficient handling of structures for RM

The objective of this task is to develop new concepts and interfaces to improve the design and handling of internal structures. This includes research on new data representations for internal structures which will directly be used for the new design tools developed within T4.2 and T4.3. Furthermore, this task will include the development of tools and interfaces to improve the general data handling for structured parts from classical CAD systems. The work will focus on techniques to efficiently handle very large STL files and on tools to generate more compact slice files as input data for the RM machines.

The different approaches to improve the generation of STL-based repetitive structures used in task 4.2 have been evaluated. This involves techniques to reduce the main memory usage on the PC during calculation, to reduce the graphics memory usage at visualizing the structures as well as to improve the performance of the structure generation itself. Furthermore, efficient data structures and interfaces for grid structures which will be used in task 4.3 have been specified. These new techniques and concepts are used within the on-going development work of Marcam's software products.

One of the new approaches is STL caching or "STL chunk technology". Many STL models are too large to store them in the memory of currently available PC's, especially when an internal structure is applied. Thus it is sometimes impossible to process such a model for RM processes. To solve this problem it is important to be able to handle STL models of arbitrary size. This can be achieved by a technique called STL caching. Instead of loading the entire model into memory at once, it is divided into chunks that are small enough to fit into the available memory.

For the model partitioning a spatial analysis is applied to the file that divides it into procesable chunks. These chunks are loaded and processed sequentially. This approach enables the processing of STL models of arbitrary size; the memory of the workstation does not limit the ability to work on a STL model. Another advantage is that the sequential processing of STL chunks can be done in parallel, which will result in a better utilization of PC's with multiple CPU cores.

The STL chunk technology has been implemented within a new batch slicing tool, InfiniSlice. Every RM process has to slice the STL file before production, but slicing a very large STL file can become a big problem for most RM processes. The new slicing tool allows hardware independent slicing of STL files with arbitrary size. The slicer operates in batch mode and works mainly independent from the available PC memory. Common slicing software has the disadvantage that the whole model must be loaded into memory. When the slices are generated, the data amount grows further, because all slices are stored in memory as well. To face this problem a dedicated slicing tool was developed that stores each slice to disc as soon as it is calculated. In addition the tool is able to operate on a model without loading it into memory completely. This was achieved by STL caching as described above. The slicing tool analyses the model file and loads only chunks into memory. Thus the generation of slice data is independent of the available memory.

The whole slicing procedure is done in parallel and making usage of multiple-cores. Using the slice tool a 1.4 GB STL file (255 mm z-height, sliced at 50µm resulting in 5000 slices) could be generated in around 8 minutes on a standard quad-core. Latest benchmark results done in September 2010 have shown the ability to process data files of more than 60 GB.

Furthermore, the STL chunk technology has been integrated into a second tool which will allow compress-ing STL files down to under 10% of the original file size without losing any information. This is very helpful to improve exchange and storage of large STL files with structures. STL file compression is not new in general, but the use of a triangle cache similar to the one used in the slicing tool will allow to compress STL files of arbitrary size which was not possible so far. The tool uses an algorithm that is optimized on compressing 3D geometry data, thus the compression rate is very high compared to classical compression methods like ZIP or RAR. In general, the compression rate is between 90% - 95% so the resulting files are much easier to handle.

The previous STL file example (1,4 GB STL file consisting of 28,7 million triangles) has been compressed down into a 78 MB file in around 5 minutes on a standard quad-core PC, which is a compression rate of 94%.

The compression result is stored as VFA file (VisCAM Facet Archive) which can be processed with all soft-ware products from Marcam Engineering. In addition, the STL compression tool can be used to decompress a VFA file back to the original STL file. The VFA file is indented to be used as exchange and archive format for large STL files. The new format contains some additional up-to-date methods to safeguard a secure file transmission and to protect the file content:

1. Protection: File access can be password protected
2. Encoding: Secure encryption with AES algorithm, CBC mode and 256 bit key length

Transmission: Automatic check sum proof to detect transfer errors, storage problems or willful file manipulations

Task 4.2 Software tools for the automated design of repetitive structures for lightweight parts

The objective of this task is to develop software for the automated design of repetitive structures based on STL files. The development uses a new data representations and techniques from T4.1. The main component of the system is an open and expandable structure database, which contains optimized basic structure geometries for different applications. The basic structures are defined by the SME partners based on their results and requirements developed in WP1. After selecting a basic structure from the database, the generation of the final structure is done fully automatic. New methods have been developed to define non-symmetrical regions and areas at the STL part. It is also possible to position and align the structures along a given curved surface. The structure design tool for the easy generation of STL based repetitive structures has been integrated into Marcam's standard build job preparation software for metal melting and sintering processes (AutoFab).

With the basic tool, memory usage and performance are increasing linearly in relation to the cell size. With the techniques developed in T4.1, memory usage and calculation time are nearly constant and therefore independent from the cell size. This means, that the new design tool is able to generate STL structure sizes, which were not possible to generate before. Slicing time increased by factor 2-3x with the new design tool compared to the basic design tool. The new approach uses 2D Booleans during slicing instead of 3D Booleans before slicing. However, the total calculation time is lower than with the basic tool especially at smaller cell sizes. One drawback of both approaches is the memory usage after slicing which is nearly identical.

Furthermore the data interface has been improved to overcome limited SLM machine accessibility. This has led to an improvement of production of very thin structure sizes around 150 um and was necessary to meet the project achievement. This is a specific solution for SLM/MTT machines; other machines are supported as much specific as possible. Marcam is in close collaboration with machine manufacturers to get more accessibility to their machines.

Task 4.3 Software tools for the automated design of lattice structures for porous parts

The objective of this task is to develop software for the automated design of lattice grid structures. Since it should be possible to use very fine structure sizes, the generation of lattice grid structures should directly be based on the slice data for the RM machine. The main component is a structure editor which will support the comprehensive, easy and flexible design of lattice grid structures with freely definable structure sizes. Optimized lattice structures for different application was developed by the SME partners and included as predefined grid structures. The new slicing routine is able to transfer information on separate volume regions within the STL part (see T4.2) into the generated slice data. They can then be used to integrate different lattice structures into separate volume areas of a part.

The task is dealing with grid or lattice structure in contrast to the STL structures used in task 4.2. STL struc-tures are "freeform" structures, which could have any shape or geometry. Lattice structures only consist of lines which have a defined diameter.

The geometrical limitation of lattice structures is on the other hand a big advantage, since it is not required to represent lattice structures using triangle meshes. Marcam has developed a new data representation for lattice structures, which stores each lattice line as a vector with co-ordinates for the start and end points and a diameter at start and end points. Therefore, the data representation is much more compact and needs less memory compared with the same structures generated as STL file. Furthermore, lattice structures are parametric structures. Since the diameter is defined for each lattice line, it will stay constant when the size of the unit cell is changed. Therefore, changing the cell size of a lattice structure will change the density of the unit cell, whereas changing the cell size of a STL structure will not change the density since all triangle elements are scaled too.

Marcam has developed a first prototype of a lattice structure editor, which is needed to create unit cells with lattice structures since there is no standard tool or exchange format available. In contrast, STL structures can be designed with any CAD system and exported as STL file. The designed lattice structures are exported in the new ACX (AutoCell Exchange) file format, which has been developed from Marcam to exchange lattice structures. Marcam has extended their lattice structure design tool, which has been integrated into their build job preparation software for metal melting and sintering processes.

The tool is able to import ACX files created with the AutoCell editor. The unit cells are then stored in the internal structure library database which now contains lattice and STL structures together. The user can select a unit cell from the library and integrated it into any imported part. It is possible to integrate lattice and STL structures in different areas of the same part. Finally, the structures are sliced and can be exported in various slice formats like CLI, SLI, F&S, CLF.

Summarized, the prototype now contains all basic features to design, generate and build lattice structures.

A comparison of the STL based approach with the parametric approach has shown that the time savings are considerably higher than 70%. But tests from the partners on different SLM machines have shown that the controlled manufacture of porous parts at SLM machines is a non-trivial task and is very difficult to control.

WP5 Surface quality

Task 5.1 Automated support removal strategies

This task consists mainly to investigate the several methods for removing support structures. The investi-gated methods include: manual removal, wire brushing, barrel finishing, sinker EDM, wire EDM, grinding, electrochemical removal, combustion deburring, cryogenic removal and milling. Information about the methods of support structure removal has been put into a software tool. In this tool a CAD-file (STL-format) of the part can be loaded and analysed. After answering a few questions an advice on the most suitable method for removing the support structure is given. The tools will give an insight in costs and an advice on possible methods. These will be ranked on quality needed and costs.

Task 5.2 Surface texturing

Marcam has developed a simple method to attach 2D bitmaps to the surface of an STL part as starting point of the ongoing development. The method at first identifies the objects within the bitmap by differencing background and foreground colors of the bitmap. The outline of the detected bitmap objects is than projected on the part surface with a given direction and distance. The part surface is then cut along the projection line and finally extruded with a defined thickness. The result can either be outstanding or engraved into the part surface.

Task 5.3 Automatic post machining

In order to allow accurate post-machining of the part surface it will be needed to add material allowance at selected positions of the part. This is typically done by applying a surface offset to selected part surfaces. A surface offset moves all mesh points of the selected surfaces by a defined value along their surface normal.

The problem with surface offsets is that the resulting part surface after applying the surface offsets can have many overlaps and intersections especially in surface areas with concave geometries. Therefore, the work to clean surface defects after applying surfaces offsets is often much more time consuming than the offset calculation itself.

To overcome these problems, Marcam has developed a new method to add material allowances to a part using voxel offsets. The new method completely recalculates the part surface after applying the new offset method instead of just moving the points of the part surface as done with the classical surface offset. Therefore, the resulting part surface is guaranteed to be error-free and no additional time is needed anymore to clean the model afterwards.

On the other hand, the new method has some drawbacks. Due to the voxel-based nature, a fixed resolution or accuracy has to be defined. This has a direct influence on the calculation time and the number of triangles. As a result the thickness of the material allowance is not constant over the whole part surface since the thickness can differ around the size of the voxels. Since the material allowance will be post-machined afterwards and the milling path will be calculated based on the original surfaces, the accuracy deviation is not problematic as long as a minimum material allowance is guaranteed at all surfaces.

At first, the new approach has been developed for tool and mould inserts which in general are post-machined to get the needed surface quality. Typically, the bottom surface of the tool insert is fixed and should not be changed. Furthermore, internal cooling channels can't be post machined since they usually are curved when SLM techniques are used. Therefore, these areas and features have to be excluded from the offset calculation.

Applying a material allowance to a tool insert is now very simple with the new offset method. The user just has to select the bottom plane of the tool and to define the minimum offset value as well as the allowed maximum deviation. All other steps like detection of internal cooling channels are done automatically. As said, the resulting part surface is guaranteed to be error-free and needs no cleaning or fixing.

Furthermore, actual automated post machining strategies have been developed. In case only support structures have to be removed, milling strategies and -parameters can be the same for each material and machine (service provider). Dedicated support structures should be involved being optimized for use as fixture for post machining. Also set point orientation is an important issue. To increase productivity an important performance improvement can be taken by placing a reference marker (rounded cylinder) on the top surface (in building direction). The quality improvement by milling high tolerance surfaces is obvious. The cost reduction obtained by switching from manual removal to CNC milling is not found, due to programming, referencing, clamping issues and the milling time. Advised is to use milling in case also other rework on the part has to be performed like drilling or milling high tolerance faces.

Task 5.4 Finishing technologies for internal structures

In the frame of CompoLight project, finishing technologies of internal structures have been studied and first experiments have been started using for internal structures by development of innovative technologies applications by abrasive flushing one and two-ways or multiflow. The abrasive flow machining process uses cylinders which extrude an abrasive media through passages formed by the work piece and tooling. Abrasive action occurs wherever the media enters and passes through the most restrictive passages. These technologies give excellent results having some special requirements for the samples preparation, as design and manufacturing of special tools and positioning devices specific for each parts shape to obtain maximal efficiency and processing yield but the surface roughness shows a highest quality and any matter due of internal channels positioning and form or configuration.

The most important element in the process is the media. It is a visco-plastic fluid with an extremely high coefficient of restitution. It is viscous pasta at atmospheric pressure but when subjected to hydraulic pressure or a sudden shear force, it reacts like a solid. It is a silicone-based material including abrasive particles. These abrasives are silicon carbide, aluminium oxide, boron carbide or diamond. The quality of the work is directly related to the media pressure, particle size of the abrasives and the volume of media extruded.

Inaccessible areas and complex internal passages can be finished economically and effectively. Automatic AFM systems are capable of handling thousands of parts per day, greatly reducing labour costs by eliminating tedious handwork. By understanding and controlling the process parameters, AFM can be applied to an impressive range of finishing operations that provide uniform, repeatable, predictable results. Anywhere that the media can be forced to flow represents a practical application.

In the study cases performed in CompoLight the surface roughness was down to 0.6 Ra, surpassing the expected achievements, while the reduction in cost when switching from manual to automated finishing was between 50 and 90 % depending on the number of parts to be processed.

WP 6 Dissemination and Exploitation

Relevant activities are described in the following sections of the report.

WP7 Demonstration

Several partner defined parts have been chosen as demonstrator cases due to their potential gain by a switch to rapid manufacturing technology. These demonstrators serve as a documentation of the technology improvements made through CompoLight and as an inspiration and appetizer for other companies. In all examples, the entire process chain has been documented and improved. Results are presented in separate deliverables, as case stories on the web and in small leaflets.

One particular interesting part, that nicely sums up the achievements of CompoLight, is 'the (Im)possible crossing'. The (Im)possible crossing is a small hydraulic part where two channels cross each other within limited space. The end results in themselves are impressive: A weight reduction of 96 % and simultaneously a pressure loss reduction of 92 %! The material consumption was thus drastically reduced while the functionality of the part was greatly increased. But what really singles out this demonstrator is the completeness of the description of the process chain. Right from the beginning, it was clear that rethinking the part with a focus on function instead of production, would potentially lead to drastic improvements. This is exactly one of the major selling points of rapid manufacturing: geometric freedom that offers practically unlimited possibilities. Thus, the design process started with the shaping of the functional volumes of the part, namely the channels. Assisted by fluid flow simulations performed in WP2, the channels were bend and stretched to give superior performance. After this initial rough shaping of the functional volumes of the part, it was time to adjust the part according to the few, but important, limitations of the manufacturing process. Assisted by the design guidelines of WP1 and WP3, there was a good understanding of requirements for support of overhangs, wall thicknesses etc. Instead of building temporary support within the channels, which would be rather cumbersome to remove, the support was permanently incorporated into the channels giving support to the overhang, while simultaneously assisting in creating a nice laminar flow within the channel. That is, the new channel design was self-supporting and even better performing than the first designs. Next, attention was put on the interfaces of the part. Interface holes for the attaching of pipes etc. was added to the part. Finally, to strengthen the part and keep everything in place, a lattice structure surrounding the part and supporting an outer box was added in accordance with the lattice recommendations of WP1 and with the help of the software developed in WP4. All through this (re)design phase, prototypes was readily produced to assist in decision makings. Finally, the internal functional channel surfaces of the finished product was treated by the abrasive flow techniques developed in WP5 leading to an even better flow.

Potential Impact:

Potential Impact

One of the major qualities of the project CompoLight was that the project has been initiated by industrial companies and created with their expressed requirements in view. The continuing involvement of all the companies during the entire project, clearly express the importance of the project for the respective companies. The choice of implementing the latest research into actual demonstrators during the project duration had the purpose of letting the partners and the European industry take advantage of the potential impacts as fast as possible, as well as create the CompoLight history. The impacts could be categorised as followed:

Impact on the European Research

The project goals and results have been presented in different forms during the last 4 years, also before it actually started. One of the major achievements of the project was much improved control over the porosity of rapid manufactured metal parts with the intention of optimizing part properties like weight or vibration absorption. Simultaneously, DTI has implemented the results of this research into a completely new product generation. An excellent example is the SME pickup production company called Ortofon: In this case, the energy absorption at certain frequencies is increased resulting in the 'best in class' pickups MC90, A90 and Expression. They have been awarded and recognised as being absolute top quality by worldwide experts.

Today, 4 years after we started to introduce these new concepts, the European research is also looking into porosity control. They have moved the focus of their research from making 100% dense parts to porous parts. The number of articles and presentations in international conferences is increasing each year.

The Danish national project F-MAT is also a direct result of the work performed in the CompoLight project. The project aim is to reduce vibrations in metal components by controlling the internal geometry of the components. The Danish funded project includes both the Danish Technological Institute as well as the German CompoLight partner Fraunhofer IFAM.

Socio-economic impact

The worldwide economic crisis started around the same time as the project; this unfortunately had some consequences on the creation of new working places in the SMEs, as the partners secured first of all their main activities and also moved some resources into the project instead of creating new positions. The European industry followed the same pattern and the implementation of the results of the project Com-poLight has been limited.

On the other hand, the results of the project supports the partner products and their services by adding higher value and creating new manufacturing concepts that supports their business models, with emphasis on agility, innovation and shorter time-to-market. Due to the results of CompoLight, most of the SMEs have gained in market position. See the paragraph below on the exploitations of the results.

Technology is still important for the European industry and rapid manufacturing offer the ability to com-pete on functionality and not only on price. New knowledge optimised products give higher competitive advantages and as the rapid manufacturing technology is quite flexible and does not need much manual work, it will help preserve European industry workplaces.

The most important impact of the project is related to the environmental aspects. The weight reduction demonstrated and obtained during the project proved that the expected impact on the fuel consumption described at the start of the project is indeed realistic (see below).

'A study shows that the amount of aluminium used in new European cars will amount to about 12 % of the weight of the car by year 2010. The weight savings achieved leads to an annual fuel saving of 1 billion litres over the lifespan of the vehicles, which is the equivalent of 40 million tonnes of CO2 emissions. An average car comprises more than 2,000 solid steel components, and it is by no means unlikely that similar weight reduction could be achieved by replacing another 12 % of these parts by lightweight components made by RM. The environmental effect of this would be the saving of another 40 million tons of CO2 emission in the cars' lifetime. With more than 12 million new cars hitting the streets of Europe each year, the annual CO2 saving, caused by the use of lightweight components, would be no less than 18 billion tons. Equivalent petrol savings would be annually approximately 8 billion litres of fuel, corresponding to 8 billion Euros.'

The CompoLight project demonstrated that the weight reductions on the hydraulics blocks from the com-pany Hydrauvision were between 70% and 95%. See the demonstrator brochures from the Partner Hydrauvision for more information. The weight reduction is not only relevant for the fuel driven vehicles. All Electrical cars need weight optimisation to improve the travelling distance with a fully charged battery. In the same way, the reduction of material consumption is contributing to a better use of our natural re-sources. Furthermore, the technology is only using the absolute necessary material in contrast to material removal technologies.

Energy losses in hydraulic components and other flow systems have also been reduced due to geometry optimisation of channels and cavities. The pressure loss through the Hydrauvision part went down with 93%, reducing the in service energy consumption. This is very promising, since more than 10% of the world's energy consumption relates to pump systems. It also nicely supplements the on-going effort in legislation-driven reduction of energy consumption that Europe has witnessed with unprecedented success in recent years. Circulators have been energy labelled and the EuP directive has set the future requirements for pumps in Europe. From 2013, standard, non-regulated pumps will be prohibited inside the EU, and after 2015, only 30% of the current A-labelled circulators will be allowed. At the same time, the transfer of these substantial technological achievements from heating to cooling, e.g. the air conditioning segment, presents an obvious business and environmental potential. The Danish company Grundfos estimates that integrated electronic control systems and sensors in small and localized 'smart-grids', so that local control units measure flow and temperature in several positions in a system and accordingly optimizes the use of the pumps will result in a reduction of 60% of the energy consumption. In the EU alone, Grundfos estimates their market potential for stand-alone circulators to 3.6 million per year for the next 5 years (for a typical sales price of 135). The development of new green technologies and production methods supports the EU targets for sustainable growth in terms of a more competitive low-carbon economy that makes efficient and sustainable use of resources and protects the environment, reducing emissions and preventing biodiversity loss.

It is important to understand that the upgrade of the European industry should not only be technological, but also consider the importance of cultural background in some of the industries. Traditional industries may indeed be very traditional in the negative sense of sticking to conventions instead of taking advantage of new capabilities and possibilities. Is a hydraulic block for example still a hydraulic block if you are changing the outer cubic shape in order to optimise functionality? Education of a new generation of engineers is decisive for the implementation of these novel technologies in the traditional European industry.

Impact on the standardisation of AM technology

The objective of increasing the quality and making the design and production of such parts efficient has been a considerable challenge. Dimensionally stable and accurate metal parts with an internal porosity or honeycomb structure and a well-defined, high quality surface is in demand in all industries. In reality, rapid manufacturing still have some way to go before it can meet industry expectations and be accepted as a valid alternative.

The RM platform, a sub technological platform under Manufuture, is an important platform where problems related to the technology are discussed. Amongst other things, the CompoLight project in collaboration with the DirectSpare and Impala projects have started the discussion about standardisation needs. The project coordinators of the two projects as well as some of the partners met at the CEN in Brussels to discuss the possibilities. This work has resulted in prioritizing standardisation as a major point in the new SRA from the RM platform.

Most of the national standardisation activities have been started by members of one of these three projects. Even a small SME as MBProto became one of the major contributors to the work of AFNOR. The German company SIEMENS and EOS from the DirectSpare project are the major contributors to the DIN normalisation and the starting point of the ISO committee. The CompoLight partner Marcam and the DirectSpare partner Materialise also got involved in the standardisation of a new file format for the technology.

The ISO committee is partly resulting from the works that has been performed during these meetings. The Compolight project is represented in this work thought the respective national standardisation units and directly participating in the creation of the ISO standard.

Dissemination activities

The dissemination activities have been on many different levels, ranging from the education of the partners to the general public body. The main dissemination activities have been done through the demonstrators created during the project. It has been very important to use real industrial cases by the SMEs to attract the interest of other companies. The dissemination activities can be categorized as follows:

CompoLight partners:

Information about the results of the different WPs of the project was shared on a secured website, giving access to all the results at any time.

If needed, the software companies Marcam and Open Engineering have made dissemination activities in the different companies to secure the accessibility of the test software to all partners. At all meetings, the focus has been on the SME partners: They have presented what they were learning from the project and their needs and request have been discussed to enable the implementation of the technology.

Machine manufacturers:

The machine manufacturers have been a special interest group. They were chosen due to the necessary of implementing advancements into their systems. This dissemination activity mostly consisted of infor-mation sharing about demands and took the form of working meetings between the different machine owners and manufacturers. The partner Marcam was one of the most active in this area, enabling and adapting its software to suit the different systems. This work also resulted in the implementation of the Marcam software in most of the machines involved in the project.

Additive manufacturing community:

The additive manufacturing community has been informed by presentations at every Rapid Manufacturing platform meeting. These meeting are held twice a year: one of them is held in Brussels, the second one in collaboration with a European conference. These updates on the advancement of the project also permit the collaboration between the 4 European projects with Additive manufacturing as subject and started at the end of 2008. The results of these meeting were also the incorporated in the important new SRA of the platform of the standardisation.

General public

The European Industry and the General Public has mostly been approached by national actions. The different companies involved in the CompoLight project have organized workshops, visits and presented the demonstrators of the project (see the demonstration activities list in the report). The Danish Technological Institute, the Fraunhofer Institute, SIRRIS and TNO have all supported most of these actions, but it is to be noticed that even small SMEs were behind some of these actions. MBProto made some workshops for the local community presented some of the results of the project in national fairs in France. Sitex 45 did the same kind of activities in Romania. The result is that the project made dissemination activities in all the 6 countries involved in the project.

A few highlights: The CompoLight project received the award for the best produced SLM part at the AEPR 2011 (Assises Europeenne de Prototypage Rapide) in Paris. The company FlyingCam was represented in the hall of Belgium at the Universal Exposition of 2011.

In the interest of all beneficiaries -the industrial ones not least - the dissemination is still continuing after the end of the project. For example, the Compolight project has been represented in the EUROMOULD 2011 fair in Germany, which is the biggest fair concerning industrial application and will also be present in the European Industrial Conference 2012 in Aarhus, Denmark.

Exploitation of the results

As the project is a targeted project for the benefit of the SME, it is obvious that the consortium has focused the exploitations on implementing the results in the SMEs. Here follow some examples of specific technological and market impact, resulting from the project.

Impact on the partners of the consortium

Even if the technology has had more than 25 years on the market, it can still be considered new. The de-gree of knowledge for most of the SMEs and Industries was quite low, still expecting the technology to be useful only for the production of prototypes. The project upgraded their knowledge to state of the art of RM/AM as production a production technology with a broad range of possibilities. The transfer of knowledge has been secured by involving partners through all the stages of the new process chain, but also by using their standard procedures and tests for the validation of the results. More important the project results have been implemented as they emerged in the SME and constituted real business opportunities for them.

MB Proto (FR): The service provider MB proto has been implementing the results of the project into their production facilities. The reduction of scrap by implementing the procedures developed under the WP2, and the work made on lightweight product in the WP3 are the major benefits for the company. Even though it is always difficult to directly make the correlation with new customers, the company is confident that they gained market share in the high technological product segment. The company also involved itself into the standardisation work made within the AFNOR and also on the international level with the ISO.

Euro Heat Pipe (BE): The Company producing Space Thermal Control Subsystems based on the use of Two Phase Systems (Heat Pipes and Loop Heat Pipes), learned a lot about the application of rapid manufacturing of heat pipes. The demonstrators made by rapid manufacturing did not completely reach the technical expectation of the company, but EHP is confident that they will be able to use these technologies in a near future. The project also demonstrates the possibility of using special materials developed by EHP. The company is continuing the investigations and tests based on the results of the project.

Flying Cam (BE): The use of topology optimisation made in WP1 combined with surface optimisation gave new advantages to the helicopter: it reduced the time to market as expected before the start of the project and it also allowed the third generation of helicopters to be more attractive also in other business area than the film industry. AM technology has become a normal production technology for the company.

Hydrauvision (NL): The specialist in hydraulics, pneumatics and mechanical drives and systems, demon-strated and proved the advantages of the technology. The reduction of weight combined with the reduc-tion of losses in hydraulics blocks gives some competitive advantages on the market. The results of the demonstrators that can be consulted on the webpages are more than speaking for themselves. Today, Hydrauvision is producing some of its products in collaboration with a partner of the project.

Marcam Engineering (DE): The German software company specialised in the development of software solutions for the Rapid Prototyping and Rapid Manufacturing (RP/RM) industry received new development projects for adaptation and improvement of the project results to specific customer needs and requirements as part of their development services. With the development made in WP4, the company became a major player worldwide in software development for the metals based technologies.

SITEX 45 (RO): The introduction of AM as one of their possible production technology is estimated by the company to give a 25% reduction of their production price on special 'micro' module electronic devices. They also expect to decrease the total unit price of cooling plates for high effect electronics in windmills by more than 27% due to the savings by redesigning the cold plate. The company is actually now working on a different project involving these technologies.

FJ Industries (DK): The Company managed to reduce the lead times from initial contact with new clients to actual supply of finished parts. The technology has been tested and used as pilot production with some customers. The control of porosity in AM technology gives them possibility of producing prototypes and product for helping in that direction.

Open Engineering (BE): The development of a multi-physics numerical simulation for the AM technology is estimated by Open Engineering as a new market possibility. The development will need much more work before its commercialization and the company is searching to continue the work. The numerical solution adapted in WP2 for the optimization of the hydraulics flow can be sold as is.

The Danish Technological Institute, SIRRIS, TNO Science & Industry and Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V obtained and developed knowledge on these technologies and products. They are selling products for their national market based on the development made under CompoLight. The project period is over, but the project itself is not finished, as some of the partners continue to work together on the next generation of products and projects.

The exploitation of the results is going further than the partners of the consortium. Dissemination and the involvement of service providers secure the implementation of the results within the European industry, especially within the SMEs which are otherwise sometimes limited by R&D resources. Energy losses in hydraulic components, time savings, lightweight and porous structures for example for filter application are definitively the major possible exploitations of the project. They are encouraging competition based on knowledge and product performance instead of price. In the long term this will help Europe to produce more innovative products.

List of Websites:

http://compolight.dti.dk/

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