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[1] **PU** = Public
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Executive summary

A growing quantity of product types in every market and every sector of industry requires huge warehouses to keep stock for spare parts, with corresponding high costs and complex logistics. This emerging problem is caused by the continuously decreasing product life time, decreasing time-to-market and increasing regulatory affairs.

Direct Spare was geared at finding a solution using Additive Manufacturing (AM) technology, enabling economically viable, on demand manufacturing of spare parts. The objective of the DirectSpare business model was for manufacturers to rapidly produce only those spare parts that are required, at a location close to the equipment that needs to be repaired. And also to improve the quality of the spare parts along the way.

Additional benefits foreseen were:

- for SME's to keep or increase their competitive position, by allowing local service providers to ensure local (EU) employment
- cost reduction on stocks and warehousing
- waste reduction as a smaller amount of parts will have to be destroyed at the end of lifetime
- environmental benefits due to reduced use of material and less transportation
- individualised spare parts for the specific users that can lead to higher margins.

To this end the project analysed seven demonstrator parts. The functional and material requirements and the cost model of the original part were taken as the point of departure. The project team analysed the possibilities to manufacture similar parts using additive manufacturing. Design, engineering aspects, material selection, production methods, quality issues and business economics of all of these parts were taken into consideration.

In the end the project delivered a number of breakthrough innovations on materials, engineering, process management and quality management. Three viable business models were developed, including requirements and constraints, that can be used as blue prints for setting up an AM driven spare part production process. To show the results of the project and indicate the benefits a real life simulation of the production of on demand, on location spare parts was taped on film.

The Direct Spare project has delivered a number of business models that allow especially SME's to provide local service. Possibilities and challenges for obtaining cost reduction on stocks and warehousing have been identified. The project also learned that to obtain waste reduction and environmental benefits, a life cycle analysis approach needs to be used. One demonstrator part indeed proved that quality improvement, based on use information, can be achieved resulting in lower costs and better margins.

Based on all findings a road map for AM has been drafted. Direct Spare underlines the possibilities and the impact of AM on the future manufacturing landscape in Europe, and the rest of the world

Leuven (Belgium) / Utrecht (the Netherlands), January 2012

A Summary description of project context and objectives

The overall objective of the project was to develop a technological and logistical system that is a fundamental and economically sustainable solution for spare parts by using on-demand production.
Structured as a highly multidisciplinary project the progress in various disciplines and processes was organised in a number of work packages.

Design and simulation
Engineers and designers needed to learn how to use 'new' materials and processes when developing or adjusting products. Computer Aided Engineering (CAE) techniques like FEA and CFD (Computational Fluid Dynamics) were used to predict the performance of products related to the used material and process. A CAE driven expert design methodology with a unique set of design rules and which can handle legacy data and scanned data was the innovation goal to achieve in Direct Spare. A Knowledge Base System to select AM technology for non experts helps the technology transfer.

Materials and RM processes
The lack of materials is often seen as an important reason for not being able to meet every application with RM.

In the project we dedicated our efforts to find practical solutions and produce market accepted spare parts using the existing materials. Both metal and polymer materials were subject to development in DirectSpare. We used two radical methods to show current day possibilities. On one hand we looked to manufacture spare parts form current materials by focussing on user requirements instead of copying design and holding on to specific materials to be used. We wanted to show that current materials can do the job, when parts are designed correctly.

Next to this widely available raw materials and material compounding were researched to match the process characteristics and wide application range of spare part properties.
We used unique expertise on 3D Printing (3DP), selective laser melting and – sintering (the most innovative RM processes available) and used project results towards selective (metal) laser melting in order to make them fully RM compatible. We closely watched the influence on the efficiency, quality and reliability of the materials.

Business models and ICT
Today's spare parts industry can be described as: high volume production, long haul transportation and extensive warehousing, resulting in huge stocks of parts that are often scrapped afterwards. In the military field, on demand production systems do exist

but these systems are very limited and too expensive for civilian use[3]. Because of the completely new additive manufacturing possibilities, the logistical and business requirements will change completely. The goal of the project was to develop at least three viable business models to use when (partly) switching over to AM.

Standardisation of processes in manufacturing, in logistics, in product and process certification, in product and business management must be developed. Legally, a wide variety of aspects was investigated: who is liable for the product, who owns the IPR related to the part etc.
On ICT level, a system needed to be developed to keep a virtual catalogue of part data.
As no reliable methods were available to assess RM processes. DirectSpare set out to design and develop quality controls and quality management for order input data, layering process quality and end part quality. A Total Quality Management system was foreseen to define the methodology that permits the evaluation, rating and accreditation of RM processes, RM materials and suppliers on a defined basis.

The resulting business models, the process-oriented standardisation for certification, the quality procedures, a (modular) data-management and tracking system and the ICT-systems for RM with traceability functions that Direct Sp[are looked to develop are really innovative.

Thus, the Direct Spare consortium started with the following 16 objectives:
1. To define specifications of the case studies (strength, durability, etc.)
2. To develop a generic roadmap for spare parts markets.
3. To create a knowledge-based system to assist non expert users.
4. To obtain RM spare parts design methodology based on FEA.
5. To create a design toolbox based on legacy data and broken part data.
6. The availability of novel RM materials (2 metals and 1 polymer) meeting the case study specs.
7. The certified capability to apply these materials in the matching markets
8. To develop 3 dedicated RM systems, based upon existing technology.
9. Determination of the impact of Direct Spare on business models and subsequent aspects related to costumer contracts, IPR, liability and potential (customer) lock-in
10. Design of a (modular) data management and tracking system.
11. Design of total quality management (systems) for RM
12. Design of appropriate standards and certifications for RM.
13. Design and validation of 3 viable business models.
14. To demonstrate three cases in real context, pursuing the industry validation of the DirectSpare concept, testing the whole supply chain where relevant.
15. To disseminate the results within the EU. It is the aim to achieve direct dissemination to 75% of all the relevant bodies in each country.
16. To exploit the results of DirectSpare through setting up a network of Research and Technology Organisations (RTOs) and industrial partners that can offer the complete DirectSpare service.
17. To define a RoadMap for AM Spare Parts

B Description of the main S&T results / foregrounds

B.1 AM Spare Part Selection and AM Spare Parts Roadmap (WP1)

B1.1 DirectSpare Case Study Selection
DirectSpare was very application driven and in work package 1 the test cases for the project where selected. Eight cases where finally chosen:

1. Siemens Tumble Dryer Drive Pedestal - The pedestal is used in tumble dryers as a motor bearing. It has the task to fix one side of the motor in the machine. Thus the motor can be rotated to strain the belt. The motor pedestal is a small assembly that consists of a bracket made from PP and an element made from PA and rubber that is glued to the bracket at four points.

2. Siemens Gas Turbine Heat Shield - The heat shielding in the shown shape has been used since the late 1990's. It operates inside of Siemens gas turbines just outside the first row of rotating turbine blade tips. There are two main functions, it shall reduce the leakage over the blade tips to a minimum and it shall protect the outer stator parts of the gas turbine from the hot gas stream.

3. Flying Cam Battery Box The battery box is one of the most sophisticated items of the platform. It includes: cells holding structure, fixation on helicopter by hanging hooks, integrated push button lock- unlocking system, ventilation, electric security insulation, integration of contactors, electronic components, sensors, aerodynamic body shape, design and image. The Flying Cam battery box is used in the Flying-Cam II UAV. Flying Cam has a fleet of 10 Flying- Cam II helicopters providing close range aerial filming service all over the world.

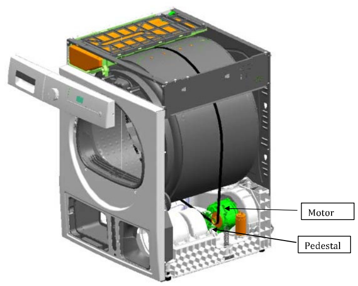
4. Flying Cam Red Gimbal. The Gimbal includes two widely separated pivot mechanisms. The tilt and roll axis intersects the center of gravity of the rotating mass (lens camera and part of the head).

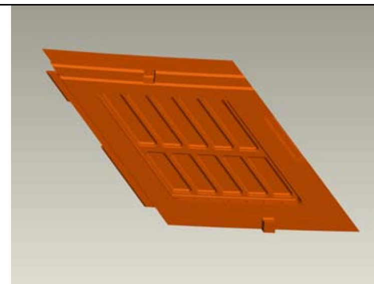
5. Eurocopter Command Support. The command support is used to physically restrict the movements of the control column in the helicopter. Since the loading of the part can be high the material must be strong and durable. There are also legal requirements for the part.

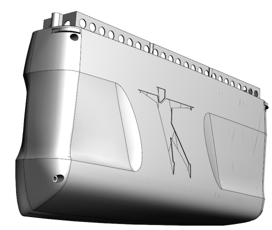
6. BMW Cover for Headlight. This classic car part covers the backside of the headlight. The reason for selection is that there still is a customer demand of the part but no tools available to produce them.

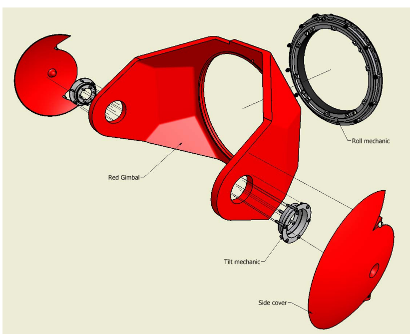
7. BMW Front Grill. This is an other classical par, a decorative and functional part of the exterior, included in the front bumper system. The part is made in aluminium.

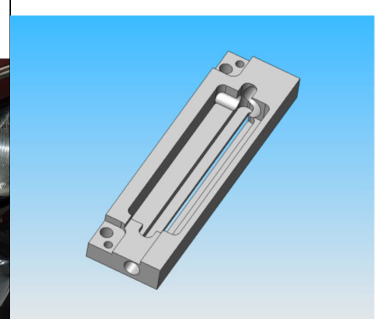
8. fcubic Holder Ink-Jet Head. The holder is used in the fcubic t20 ink jet test equipment. The holder positions an inkjet head in the equipment and allows for adjustment of the head. It is also used in the fcubic c300 equipment. The part is made in stainless steel.











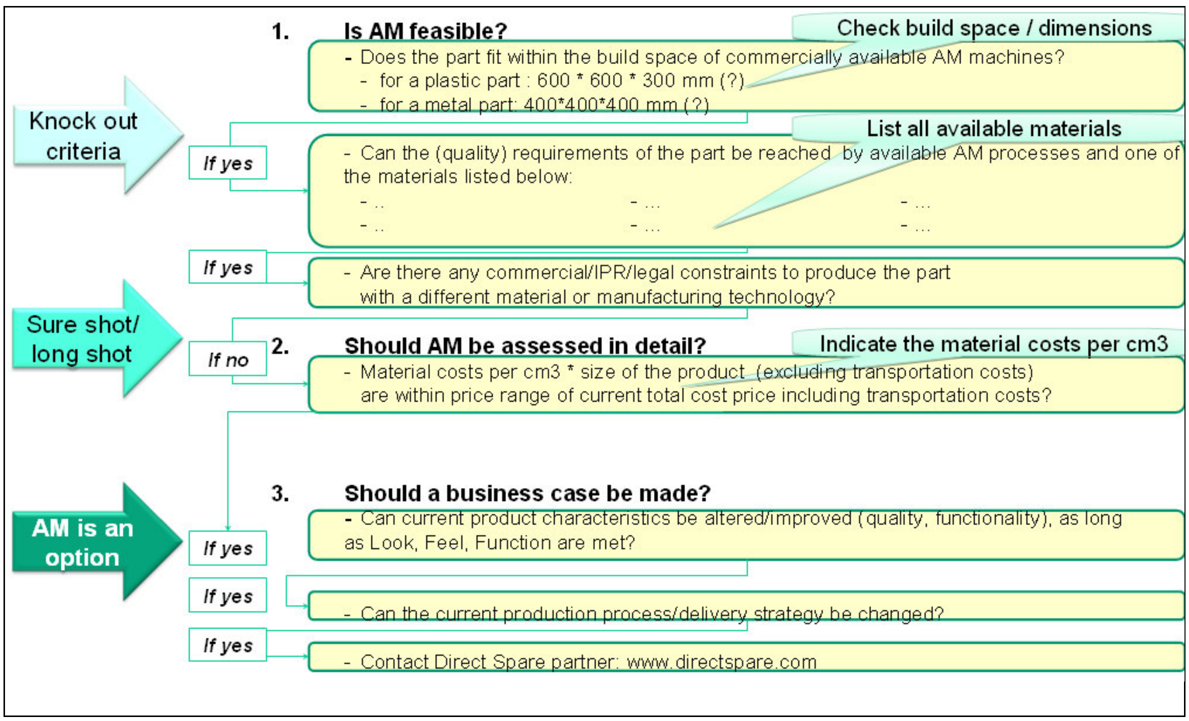
B.1.2 AM DECISION MODEL FOR SPARE PARTS

Beyond selecting a limited set of cases for the project we also developed a selection methodology blater on in the project and based on results from the project.

To assist a design engineer or purchasing engineer two selection models have been created, one simpler version for non-specialists and one more complete model for a specialist within the AM-field. The models give an understanding for which cases AM is a viable option to produce spare parts.

Non-Expert Approach

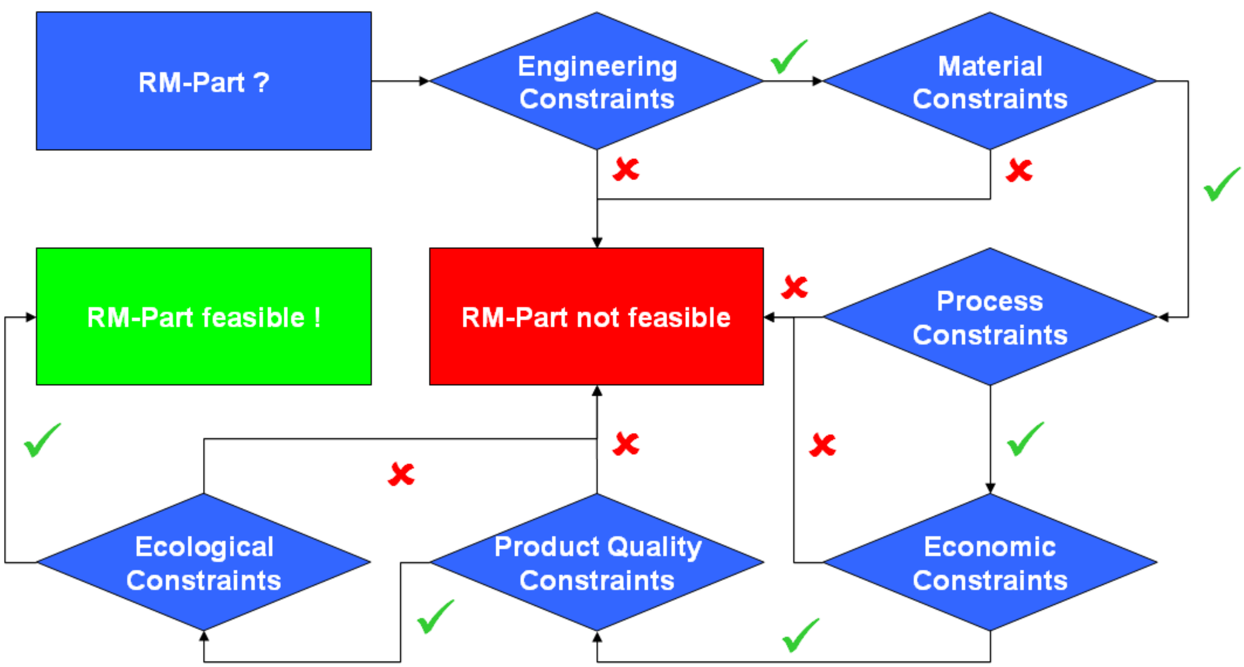
Before considering in-depth analysis of possible decision making it seems appropriate and more tangible for the non-expert to derive a rather simple set of questions for a first-hand opinion on the central question whether AM is viable or not. The flow chart depicted in fig. 1 which imposes very basic questions which can be answered with minimum amount of knowledge about AM technology, i.e. at management level or at a very early stage into the project. These questions comprise the feasibility with strict knock-out criteria as well as simple, however important and therefore mandatory considerations from production engineering such as product quality and manufacturing cost and time. The information needed at this stage can typically be assessed from OEMs, i.e. AM machine manufacturers, who typically provide data sheets on process performance capabilities and related material properties.



Refined High-level Approach

It becomes quite clear that the approach introduced above for non-experts will only suffice for first order estimations. When a project on production with AM technologies evolves more obstacles might be disclosed along the way before a decision can be taken. These obstacles are typically not merely questions on a rather detailed level, which need to be answered, but also actions that must be taken in order to acquire such answers. If e.g. a decision depends on material properties as they result from the AM process then intensive material investigations might be necessary before a final overall decision can be derived. In this specific case this could easily be a matter of more than one-year project time before the evaluation is complete!

In order to account for all potential questions and issues that could possibly arise during an investigation project of assessing the feasibility of AM as a sound and solid manufacturing route for a given product, the high-level approach has been divided into six major groups. These groups form the basis for an extensive questionnaire each of them addressing issues targeted at a specific group of experts. Namely, the groups represent engineering constraints, material constraints, process constraints, economic constraints, product quality constraints and ecological constraints. If a single group yields a definite knock-out then feasibility is not given, highlighted in figure 2.2 in a red decision box. If, however, none of all the constraints show critical limitations then feasibility is given. Since the group of experts will act on behalf of the management board the level of these six major groups is described as management level in the questionnaire developed here.



B.1.3 GENERIC ROADMAP FOR SPARE PART MARKETS

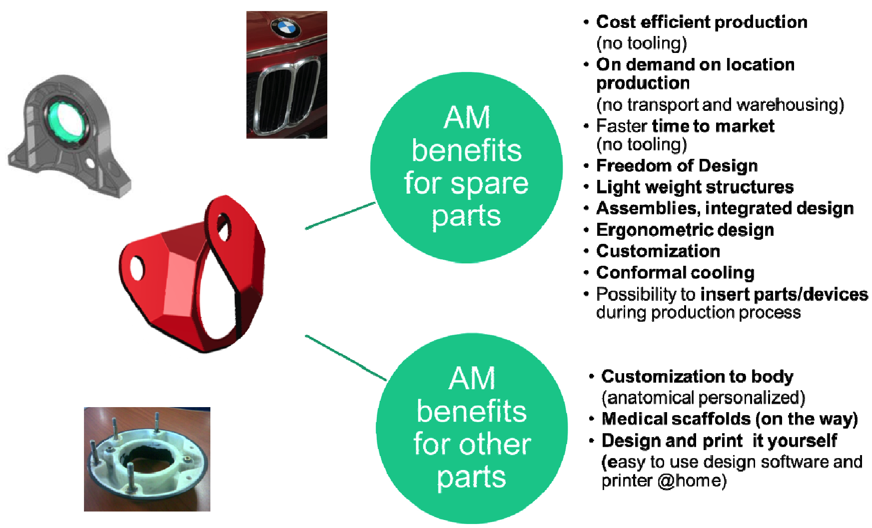
For the involved consortium in the Direct Spare project it was already clear for years, that there is a market opportunity for Additive Manufacturing (AM) spare parts. Nevertheless, an in depth understanding of the potential of AM for all relevant spare parts markets was not existing. Therefore the roadmap dedicated for AM spare parts is developed within the Direct Spare project.

The generic roadmap for AM spare parts starts with the market side of AM spare parts, and identifies barriers as well as and further research & development (R&D) opportunities. This will be matched with the roadmap of the European RM-platform.

AM Roadmap

The AM market in terms of current revenues and state of the art of the technology was investigated and a roadmap for AM (Spare Parts) has been developed (see also B.5). The benefits of AM for spare parts were described as well.

The spare parts market is a big market. It represents an equivalent of 2-4% of the total investment in industrial equipment, creating a multi-billion market worldwide. For instance, the EU market for automotive spare parts and after sales servicing totals at about € 80 billion per year. Therefore it is a very interesting market for AM.
AM technologies offer several benefits for spare parts (see figure below).



Market requirements

In the Direct Spare project four interesting spare parts markets are selected: aerospace, automotive, domestic appliances and the energy industry (energy producing equipment/installations). For these markets an in depth analyses was presented and the potentials for AM in these markets are discussed. The results will probably give insight into the potential of AM for other markets as well.
The current market requirements in the four markets are visualized in the figure below.

Theme	Aspects (requirement/USP)	Aerospace	Automotive	Domestic Appliances	Energy Industry
Costs	Production costs	⇨	⇧	⇧	⇨
	Total costs for customer (order-delivery)	⇗	⇧	⇧	⇨
	Total Cost of Ownership (incl use phase)	⇗	⇧	⇗	⇗
Time (logistics)	Production time	⇨	⇗	⇗	⇨
	Delivery time	⇗	⇧	⇗	⇨
Environmental	Energy usage/carbon footprint (total life cycle)	⇨	⇗	⇨	⇨
	Material usage (total life cycle)	⇨	⇨	⇨	⇨
Design	Weight of part	⇧	⇗	⇘	⇨
	Part life cycle (durability)	⇧	⇗	⇗	⇧
	Complexity (design of parts)	⇧	⇗	⇘	⇗
	Aesthetic	⇘	⇨	⇗	⇩
Part Quality	Material properties	⇧	⇧	⇗	⇧
	Surface quality	⇗	⇗	⇧	⇨
	Residual Stresses	⇗	⇨	⇨	⇧

⇩	⇘	⇨	⇗	⇧

Least important ⟷ Most important

Barriers

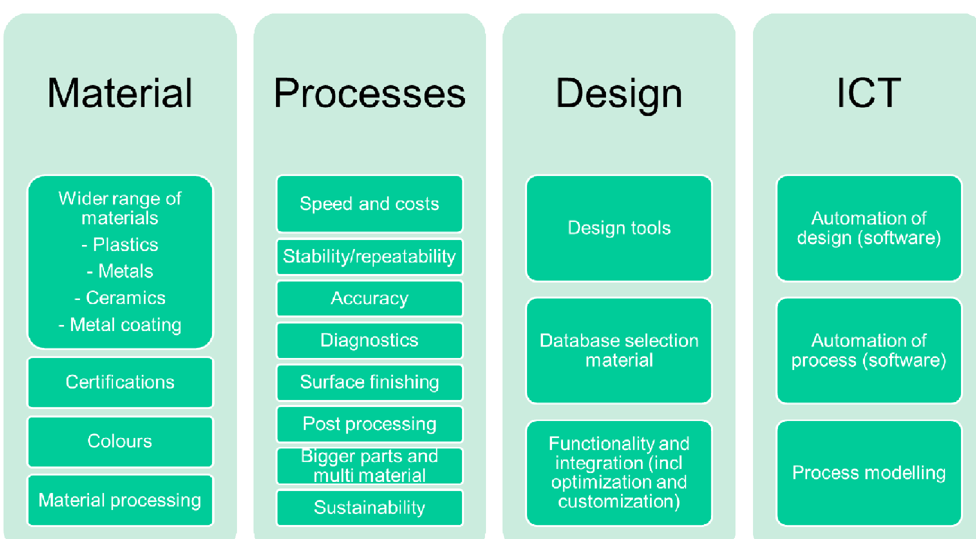
Currently still barriers exist which prevent AM from breaking through in the spare part markets. These barriers exist on different levels; process, system and material, production integration and plant integration level. The most important market requirements are linked to the barriers as well.

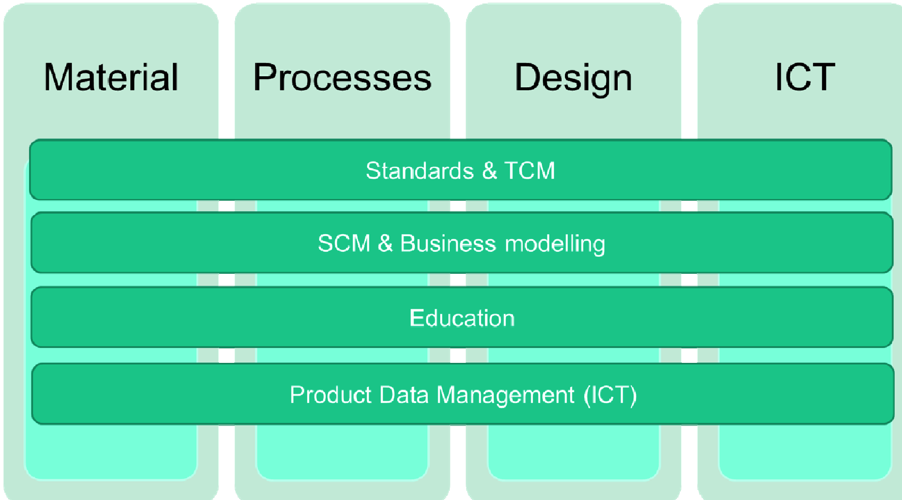
	Automotive	Domestic Appliances	Aerospace	Energy
Cost	X	X		
Function			X	X

Cost	Quality	Time	Design (incl extra AM benefits)	Others
• Often not competative (quality dominant cost, but also material, process and engineering cost important)	• Performance not stable (repeatability) • Performance often not meeting requirements (accuraccy, finishing, etc.) • No full understanding of material and processes (modelling)	• Process speed to low • Supply chain adjustments neede	• No design tools • No automation of design (CAD, modelling, simulation)	• Availability of materials • Automation of process and data management (influence other aspects as well)

Future R&D opportunities

Finally, the future R&D opportunities (that influence the barriers) to fully grasp the potential of AM spare parts, are presented. See the two figures below for the overview of the R&D opportunities.





B.2. Design and Engineering of AM Spare Parts

The work was split up into test case specific activities, which were carried out by various partners, whereas the generalisation of this work for generic Direct Spares development was done by BPO and Materialise. The initial goal of WP2 was to develop a generic design methodology for Direct Spares. Ultimately, this could lead to e.g. fully automated, on demand, local production of spare parts utilising additive manufacturing (A.M.) technology. Several adaptations to the initial plan were implemented, to make sure that the followed path would lead to a design system capable of designing both technically and economically feasible Direct Spare parts. The adaptations are described in the deliverables and are briefly repeated in this document.

For Work Package 2, the biggest challenge to deal with was the economical feasibility. Current design tools (CAD, FEA) were developed during the seventies, when labour was cheap and equipment was expensive, yet limited in its capacity. Typical features of classic tools are listed below.

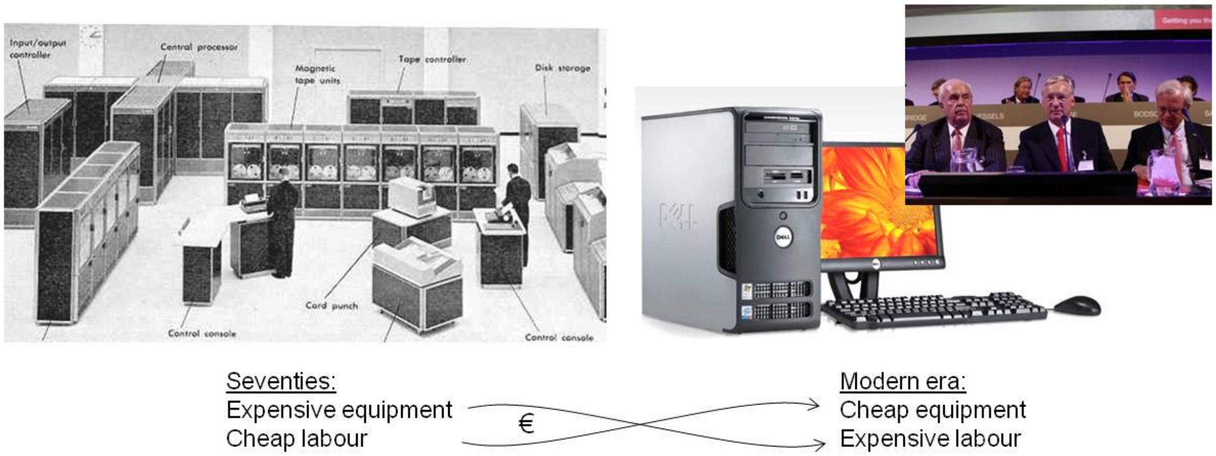
CAD from the seventies:

- The geometry of the product is represented by subsequently points, curves and surfaces. Closed surfaces represent a solid geometry. Curves are mathematically interpolated between the points, surfaces between the curves.
- Using mathematical interpolations avoids problems related to hardware limitations: too many point definitions require too much hardware resources.

FEA from the seventies:

- The number of elements is very limited. Therefore, all sorts of smart workarounds are invented to make FEA as versatile as possible: second order elements, P-type elements, shell elements.

- Results of FEA calculations are printed in numbers. Experts analyse these numbers and interpret these.



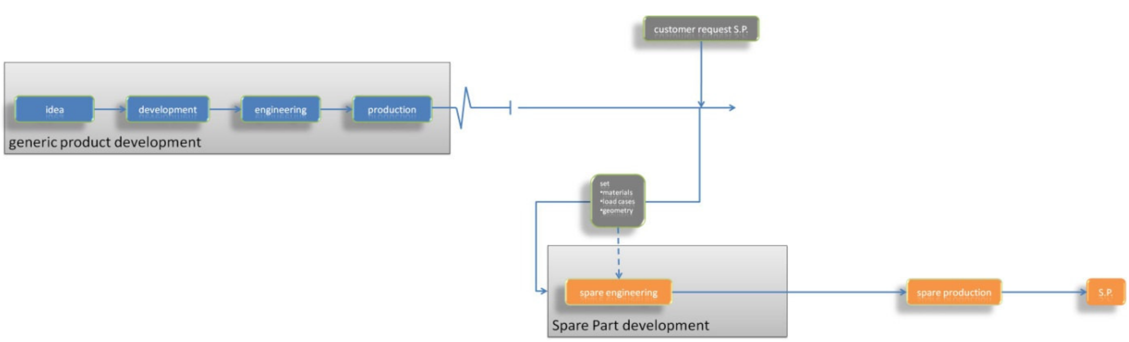
During the nineties, a major change took place: computing technology became faster and faster, whereas the wages of expert engineers benefitted from the economic perspective. Today, this trend continues to develop. However, modern CAD and FEA tools still have their roots in the seventies and still require control of an expert engineer.

That puts Direct Spare to the following economical issue: expert engineers are so expensive that their efforts can only be applied to a relatively large series of products, as so to spread costs. Since the number of product copies is expected to be very limited for Direct Spares, this renders the classic CAD and FEA tools almost useless: they are too expensive.

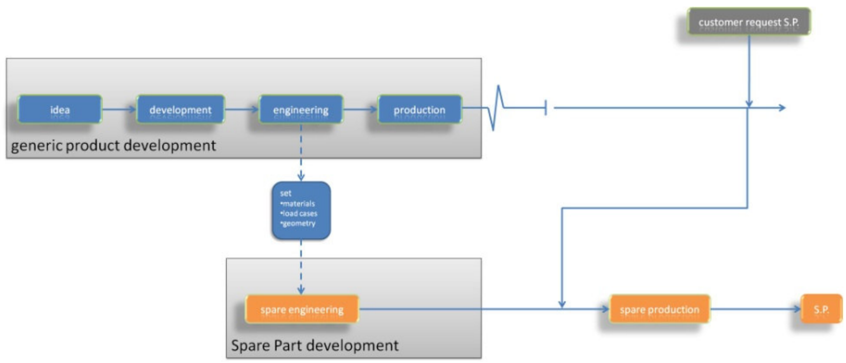
For Direct Spare, a new design method had to be developed. The following strategy was applied:

- Development of the Direct Spare must be timed carefully.
- Automate as much as possible.
- Transfer labour to the (non-expert) customers.

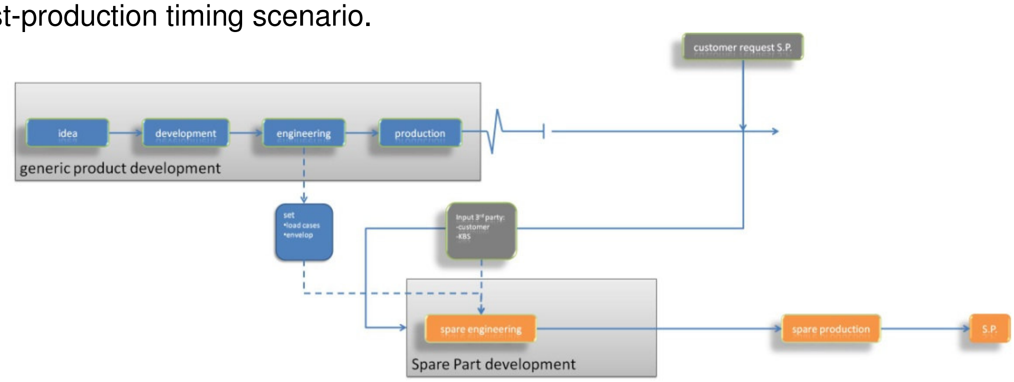
The reason for careful timing is clarified with the following diagram. The most obvious Direct Spare development timing would be post production timing: as the spares on stock run out, a Direct Spare is developed. This development process would be too expensive when classic CAD and FEA tools are used.



Alternatively, the Direct Spare can be developed simultaneous with the "normal" part, as shown below in the pre-production timing diagram. The drawback of this is that a part is developed for production means that are ten years old by the time the parts have to be used. Additive Manufacturing as process, and its materials, are developing fast. It is expected that technology has moved on so much that the Direct Spare development might have to be done twice.



As "best of both worlds", WP2 proposes a third timing scenario: flexible pre-production timing. During the development of the "normal" parts, the Direct Spare is pre-engineered. When the Direct Spares are required, the design is finished at a much lower cost than in a post-production timing scenario.



The automation of tasks researched within WP2 can be split up in two fields of activity: CAD automation and FEA automation.

CAD automation means the introduction of a new method for describing and editing digitised geometry. Instead of using traditional points, curves and surfaces, partner Materialise introduced Digital CAD, based on describing the outer surface of a part with a large amount of triangular facets (permitted by the latest computer technology: no more hardware limitations). Digital CAD has many benefits for the redesign process that is associated with Direct Spares:

- To get from the point cloud of a 3D scan to a CAD-file requires (automated) triangularisation only and not a complete (manual) reverse engineering process.
- Making small modifications to a Digital CAD-file is relatively easy and quick (in other words: low cost) with the tools that were developed within WP2.
- Traditional CAD describes only the outer surface of a (solid) product. This prohibits the introduction of microstructures, producible with Additive Manufacturing. WP2 developed tools for Digital CAD to process internal microstructures.

The automation of FEA requires a new design method, because traditional FEA heavily relies on expert engineers. For the expert engineer, traditional design means composing a list of specifications, selecting the right material and letting the computer do FEA calculations. The results of the FEA calculations are again checked by the expert engineer to decide on the suitability of the part to deal with the load cases. The expert engineer then decides if material should be added (and where / how much), based on subsequent FEA calculations. Automation of the traditional design system means automation of the decision making processes. Alternatively, shifting the decision making to the customer in unrealistic: the customer does not have the expert knowledge. Letting the customer decide on the FEA details can therefore only lead to disappointing results.

Instead of developing complex decision making algorithms, partner BPO developed a new product design method instead: *Copy Specifications*, or *Copy Original Part Properties*. What this means is that (automated) FEA simulations are done with unit loads.

1. The customer defines (uploads) the current product to the design system. The customer also defines where it is fixed to other parts during its functional use. The customer also defines the current material.
2. The design system subjects the original part to FEA simulations with unit loads, on each fixing point. The response of the fixing point while the others are fixed in space (its strength and its stiffness) is monitored and stored.
3. Based on the results, the design system suggests an A.M. material to the customer and optimises the geometry to match the responses of the original geometry.
4. The result (output from the design system) is an optimised 3D CAD-file, together with a material choice, for a product that has the same strength and stiffness as the original part.

The benefits of this new design method is that the customer does not need to have expert knowledge in the field of product development, and that the design system does not require knowledge of the requirements of the new part. Decision making is limited to the minimum.

The newly developed tools and method were tested by all partners on six test cases: a tumble drier bracket (Siemens), a gas turbine heat shield (Siemens), a flying camera bracket (Flying Cam), a helicopter command stick support (Eurocopter), a head light cover (BMW) and a front grill (BMW). The many results can only be summarised here, the reader is kindly referred to the periodic activity reports for more specific test case information. Although the development work is not quite finished, the achieved results are promising.

The concept 'Direct Spare' requires a major change to traditional CAD and FEA tools to become economically feasible. This will require a cultural change too: expert engineers will have to design the design systems instead of products. Within the FP7 project, a first step was made. The results of this work will be continued in spin-off developments.

B.3 AM Material Development

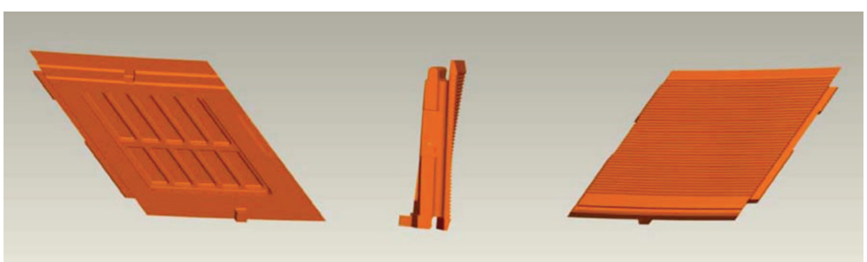
WP3 focused mainly on development and qualification of materials for selected application cases and production of these parts by laser sintering.

The following table shows the selected application cases and the corresponding materials and project partners.

Application Cases	Material	Company
Heat Shield	EOS Hastelloy (metal)	Siemens
Gimbal	VESTOSINT Z2634 (polymer)	Flying Cam
Headlight Cover	VESTOSINT Z2634	BMW
Front Grill	EOS Aluminum AlSi10Mg	BMW

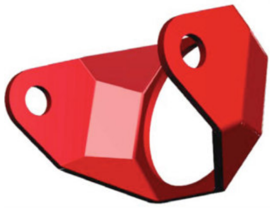
The materials have been used in the initial qualification and certification phase and the polymer was further improved for headlight covers. Here several new charges of VESTOSINT Z2634 have been prepared at Evonik in pilot scale and subsequently tested at BMW and EOS in order to improve the balance between mechanical and processing properties. Unfortunately the requirements concerning dimensional stability and warpage could not be fully met.

For the application *heat shield* Hastelloy X has been applied instead of the originally used Inconel 939 alloy.



The test items have been produced and were subject to in-depth analysis. Although significant improvement could be seen, at this time a complete fulfilment of all requirements for this application could not be obtained. Siemens is considering using the results of this project to develop Inconel 939 in future for the application.

The qualification of VESTOSINT Z2634 for *gimbal* applications, here for a fliging camera, was very successful.



Visual inspection showed an extremely good quality: no details are missing, no visible warpage and a surface finish for good paintability. The good paintability could also been demonstrated by an actual test. Stiffness was excellent and the part retrieved this original geometry even after application of heavy loads. Although some small deviations of the parts dimensions after its production had to be noted assembly into the sphere main shell could be achieved without any problems. In the final ground test with an actual camera the whole sphere accepted the fast movements without resonance effects. That means that the stiffness of the whole assembly is adapted to the electronic stabilisation system, load as in common use. Overall it can be concluded that after some design modifications even standard PA12 fulfils all requirements. Thus, there is no longer the need to development a new material.

Several processing trials had been performed and a *headlight cover* has been produced and tested.

It was possible to improve the results of the trials, although also some setbacks had been experienced. At the final headlight cover production trial, is was observed that the material meets mechanical and processing requirements, only the high visual appearance requirement for this visible part is not met.
In the scope of this project it was not yet successful to compose and upscale a material that fulfills both processing and mechanical properties. But it should be mentioned that the upscaling in general seems to be possible and could be addressed again when the customer's demand arises. The availability of larger quantities of optimized VESTOSINT Z2634 shall not be any problem.

The aluminium based material for *front grill* applications developed by EOS meets the mechanical and processing requirements.

However, the high requirement of this application case concerning surface quality and visual appearance was not achieved. As this material proved its ability to produce parts by laser sintering and meeting mechanical requirements, other potential application cases can be expected, where the requirements on visible appearance are lower (no visible parts).

In general the results show that it is possible to produce parts by laser sintering from different materials and to achieve considerable properties that definitely open possibilities of application or even qualified already for one of them. Although, material qualification could not be achieved in all selected application cases by the used materials, the success of the research and the considerable improvement of the state of the art caused by this project is evident.

B.4 AM Process Development

This paragraph describes some of the publishable results achieved within work package 4 (WP4) of the DirectSpare project. There are other results that currently have to be considered confidential within the consortium. Only the content of this report can be used for dissemination purposes.

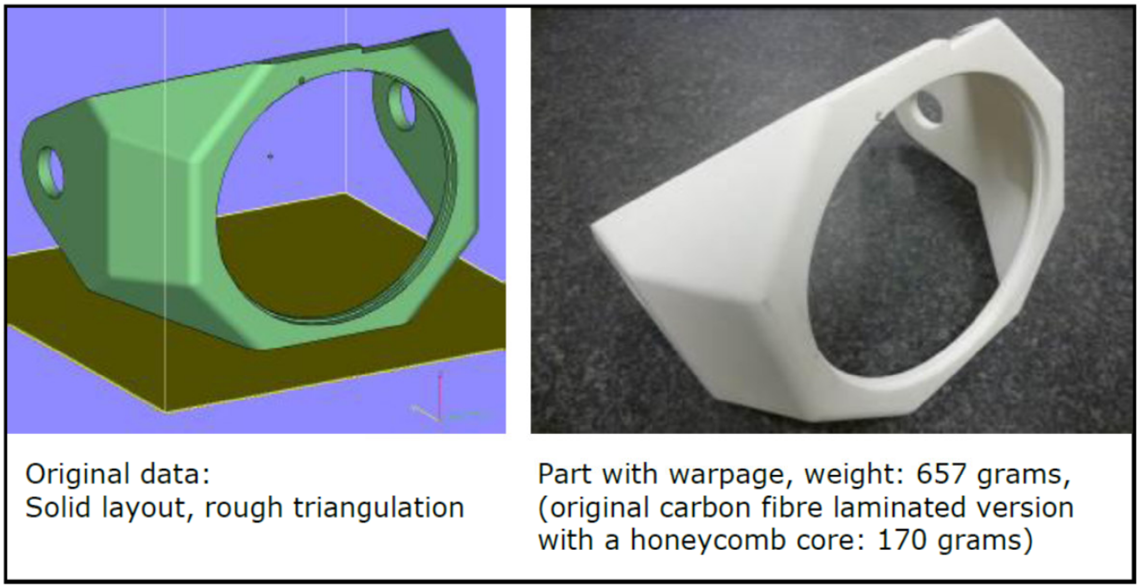
Improvements achieved for plastic applications (case studies)
Along with hardware modifications (e.g. the EOSINT P 395 - surface module) the part quality in matters of accuracy, surface and detail resolution was improved with subsequent arrangements in order to meet the case studies specifications:

- Change of part design or re-design of part from “conventional” to AM suitable using internal structures with optimized weight/performance ratio (see figures below)
- Optimizing part building orientation
- Development of new exposure strategy and parameters

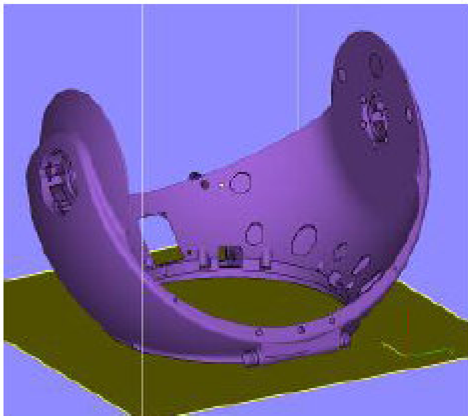
Several parts have been sent to the case study owner for further investigation, one of them could already be proven valid in real flight testing.

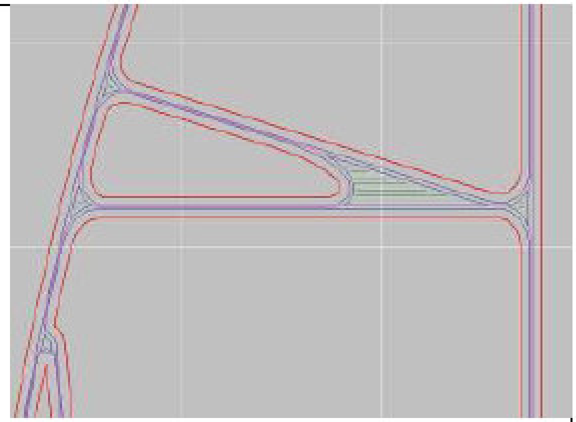
Original data:

- Solid layout, rough triangulation
- Part with warpage, weight: 657 grams, (original carbon fibre laminated version with a honeycomb core: 170 grams)



Red Gimbal case study – original STL design (left) and solid part built in PA2200 (right)

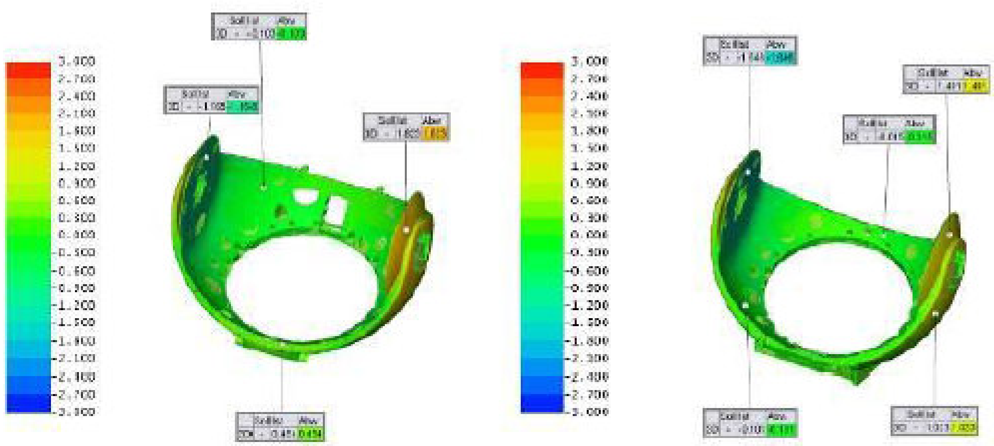




optimized data: honeycomb layout, fine triangulation

Exposure layout of internal structures

Part showing good resolution/roundness of small bores and surface quality; weight: ~273 g



very good dimension accuracy, low distortion (~2 mm), wall thickness according to nominal size (~1 mm)

Case study built in PrimePart DC –orientation (upper left), exposure layout PSW (upper right), part pictures (centre) and accuracy analysis (lower)

Process improvements achieved for metal applications (case studies)

AlSi10Mg

Several improvements could be realized in order to meet the corresponding case study specification.

Reducing distortion by preheating during laser-melting

Partner ILT has performed the work for the case study and has implemented a preheating device in its EOSINT M270 system.

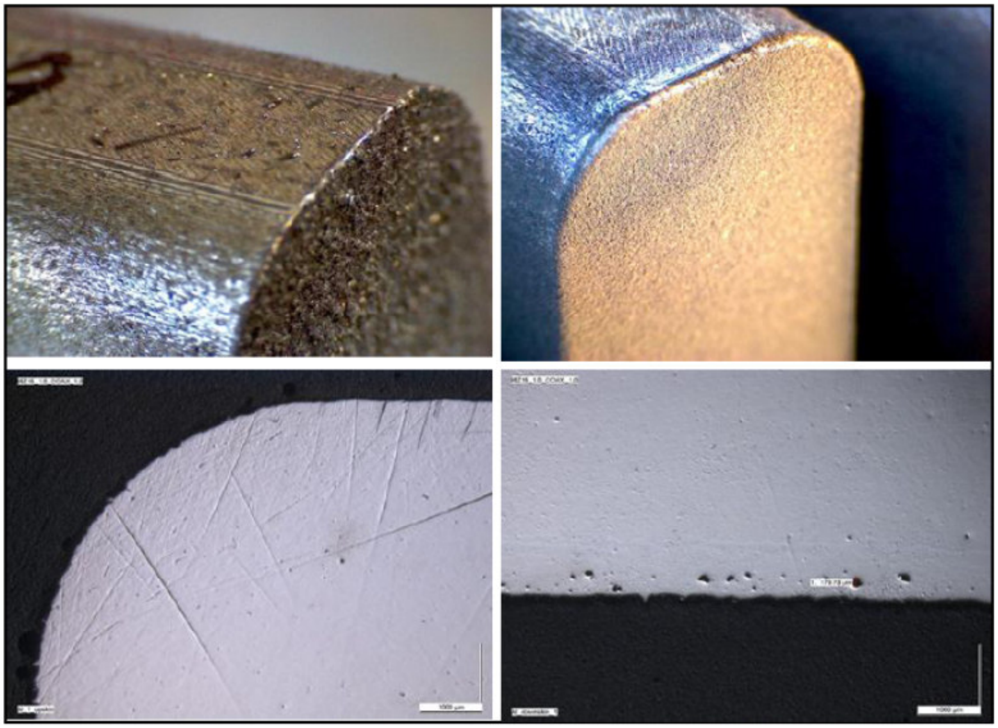
Independent of the material thicknesses, distortions can be reduced by using preheating in SLM test geometries made out of AlSi10Mg. Due to the preheating, the distortions of the test geometry (twin cantilever with bar thickness of 0.5 mm) are reduced from 10.6 mm (without preheating) to nearly zero (±0.2 mm) at TV = 250℃ within the scope of the measurement accuracy. The results demonstrate that the distortion is dependent upon bar thickness. There are the larger distortions on the test geometry with the smallest bar thickness, 0.5 mm, than on the test geometry with the largest bar thickness, 5 mm.
The first significant reduction of distortion (up to 3 mm) appears from a preheating temperature of 150℃ for all bar thicknesses in comparison to the distortions without preheating. At a preheating temperature of 250℃, distortions can no longer be ascertained within the scope of the measurement accuracy, independent of bar thickness.

In addition to the reduction of the distortions, the preheating prevents cracks in the component caused by stress, which can lead to the tearing of parts of the test geometry built without preheating.
From a preheating temperature of 200℃, the hardness of the components manufactured out of AlSi10Mg decreases. With 90 HV 0.1 and at a preheating temperature of 250℃, the hardness is, however, still higher than the required minimum hardness of die-cast components made of the material AlSi10Mg according to DIN EN 1706.
From these results, it can be derived that a preheating temperature of 250℃ is appropriate for manufacturing components out of the material AlSi10Mg with SLM free of defects, with process reliability; in addition, this temperature prevents distortions completely.

Surface improvement by laser-melting parameter adjustment

Based on the EOS standard setting for an EOSINT M 280 system with 400 W laser the surface was improved by verification of the parameters exposure speed, laser power and hatch distance.
Adapting the results into a new parameter setting, conclusions are (figure below):

- surface roughness reduced from former Ra of 15-19 µm to a new Ra of 4-8 µm
- a higher porosity in the surface area
- 25% increased build time compared to the standard 400W parameters



Surface and porosity with standard (left) and new parameter setting (right)

Process on EOSINT M280 system with 400 W laser power

With the new M280 system becoming available, some of the new features like the 400 laser option and a modified gas management were used to evaluate their influence on building speed, mechanical properties and surface quality.

AlSi10Mg coupons built using a 400W laser setup in the M280 show almost no difference in the mechanical property values in horizontal and vertical orientation of the samples. The part strength, compared to the beginning of the development, could be increased by 15%!

Porosity could be improved from 0.5 % on M270 with 200 W laser power to 0.05 % on the new M280 with 400 W laser power, while volume rate (build speed) could be doubled. Density of the parts could be increased from previously 2.57 g/cm³ to 2.68 g/cm³.

Hastelloy X

Process was developed on an EOSINT M 280 system with a 400 W laser. The table below gives a comparison of the mechanical properties of an EOSINT M 270 with 200 W laser with those achieved on a 400 W system. All samples were tested as manufactured. A slight increase in the tensile strength could be achieved.

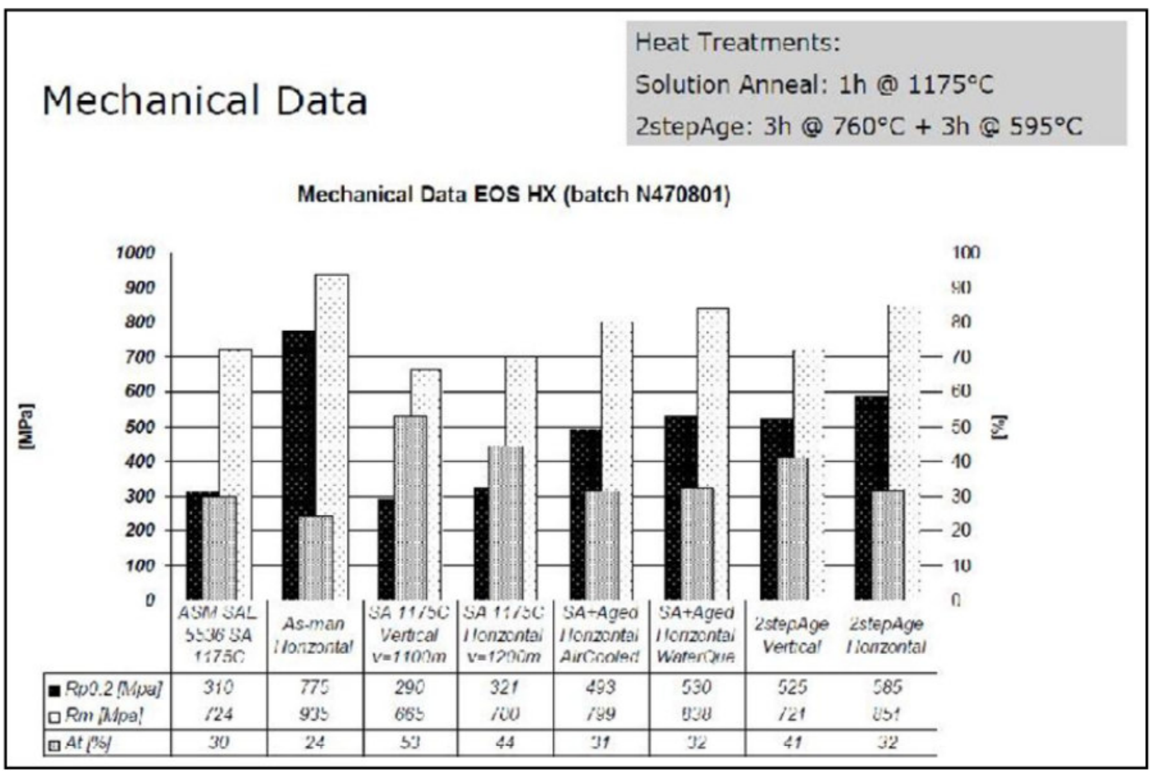
		EOSINT M 270 (200 W) September 2010	EOSINT M 280 (400 W) January 2012
property		**value**	**value**
Tensile strength	R_m	725 +/- 50 [MPa]	750 +/- 50 [MPa]
	$R_{p\ 0,2\%}$	580 +/- 50 [MPa]	600 +/- 50 [MPa]

In following table the improvement achieved for the surface roughness is shown.

	EOSINT M 270 (200 W) September 2010		EOSINT M 280 (400 W) January 2012	
	Ra [µm]	Rz [µm]	Ra [µm]	Rz [µm]
Hast X 0°	10.44	42.55	7.65	37.77
Hast X 30°	23.12	85.47	17.01	80.49
Hast X 45°	19.59	76.12	16.18	69.82
Hast X 60°	16.34	67.83	13.64	58.91
Hast X 75°	15.63	56.71	11.22	52.30
Hast X 90°	12.54	49.39	8.58	51.12

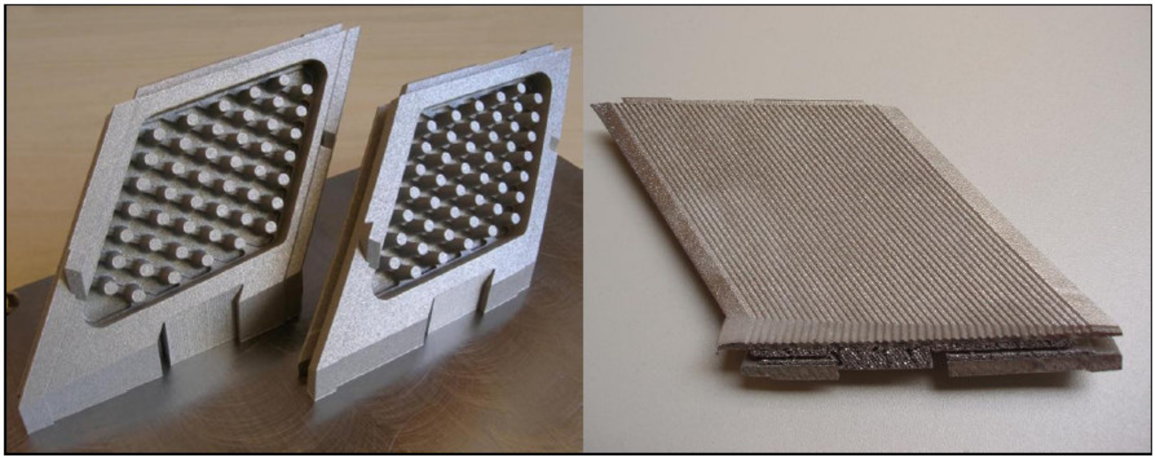
Comparison of the surface roughness

The influence of build orientation, cooling and heat treatment is shown in the figure below.



Influence of heat treatment, build orientation and cooling on mechanical properties of HX samples

The case study based on the re-designed geometry was built on EOSINT M 280 with 400 W in 2 different build orientations using all the settings developed (see figure below).



Re-design of the case study built in HX

B.5 AM Total Quality Management , AM Data Management and Control System and AM Spare Part Business Modellen

The Direct Spare project assesses if RM-produced spare parts (RM-spares), meaning produced on demand and at a location close to the equipment that needs to be repaired, are an economically viable option.

Distinct differences exist between large series and small series parts with regard to spare part economics. Therefor the business model as well as the data management, total quality and a standards and certification process were assessed and outlined, with the results described in short below.

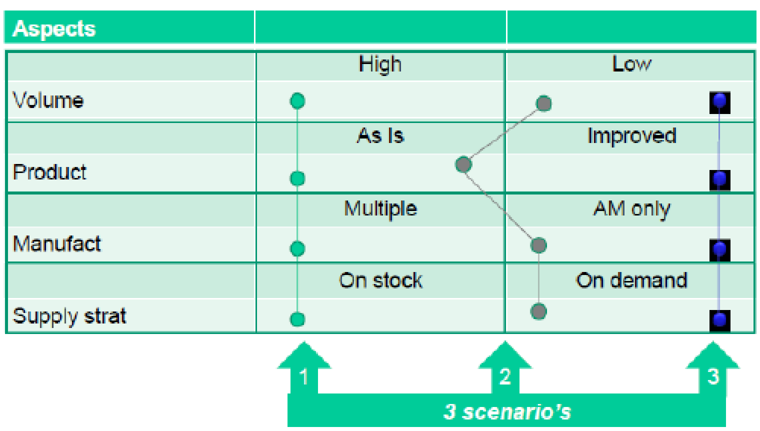
The Direct Spare project focuses on finding a solution for the growing quantity and variety of product types on the market, requiring enormous warehouses to keep stock for spare parts, with corresponding high costs and complex logistics. This issue is becoming more important in the light of decreasing product life and time-to-market for products, paired with increased regulatory requirements. Using Rapid Manufacturing (RM) presents a solutionwith the following expected advantages:

- huge cost reduction on logistics and tooling
- waste reduction
- retained or increased competitive position of companies (especially SME's) with business models aimed at this way of spare part supply
- local service providers ensure local (EU) employment.

When 'on demand, at location' production is possible, Direct Spare will have substantial impact on current business models. A wide variety of subsequent aspects regarding customer contacts, Intellectual Property Rights, liability and potential customer lock-in needs to be investigated. A comprehensive questionnaire was setup regarding all these aspects of spare parts. Via this questionnaire we analysed for each step in the value chain quantitative data (volumes, costs, margins) and also qualitative data; e. g. Is copying allowed? Who is responsible when the spare part breaks?
Based on the outcome of the questionnaire and the follow up discussions we have had, initial conclusions are that, related to spare parts.

Advantages	Roadblocks
+ RM allows for flexible set up of the production process; + RM allows for lower stock levels and balancing end of life stock positions; + RM can help decrease the number and distance of transportation movements, decreasing also the associated costs and environmental aspects; + RM can deliver improved products leading to less breakage and thus less spare parts required; + RM will lower the tooling costs; + Centralised IT/data management is required. But as in many companies these developments are underway. RM is rather underlining the necessity of centralised IT, than that it requires new (and costly) systems.	- Not all spare parts can be produced with RM: material constraints, size/dimension constraints; - RM requires investments in new manufacturing technology and possible increased depreciation of currently used systems and tooling; - Using two different manufacturing technologies for producing one and the same spare part is mostly not cost effective; - To obtain full advantage of RM new business models need to be accepted (by all partners in the value chain!); - To allow for RM compliance with legal (warranty) and IPR aspects is required; - Quality control systems need to be updated to cope with the new business models used (e.g. local production by random RM-service bureaus).

So based on the findings we developed 3 scenario's which were validated. The decisive elements in which the three generic AM-enabled business model differentiate are summarized in the picture below:



No matter what scenario a data management and tracking system is required using innovative software solutions to deal with real manufacturing as opposed to prototyping. The data management software forms an indispensable component in the total DirectSpare concept because it enables worldwide ordering and local order manufacturing and management, it contributes to the total quality management system and part quality with full physical part traceability, it helps in distinguishing original parts from illegal copies and it automates large parts of the order and file handling which makes the DirectSpare concept more economically feasible.

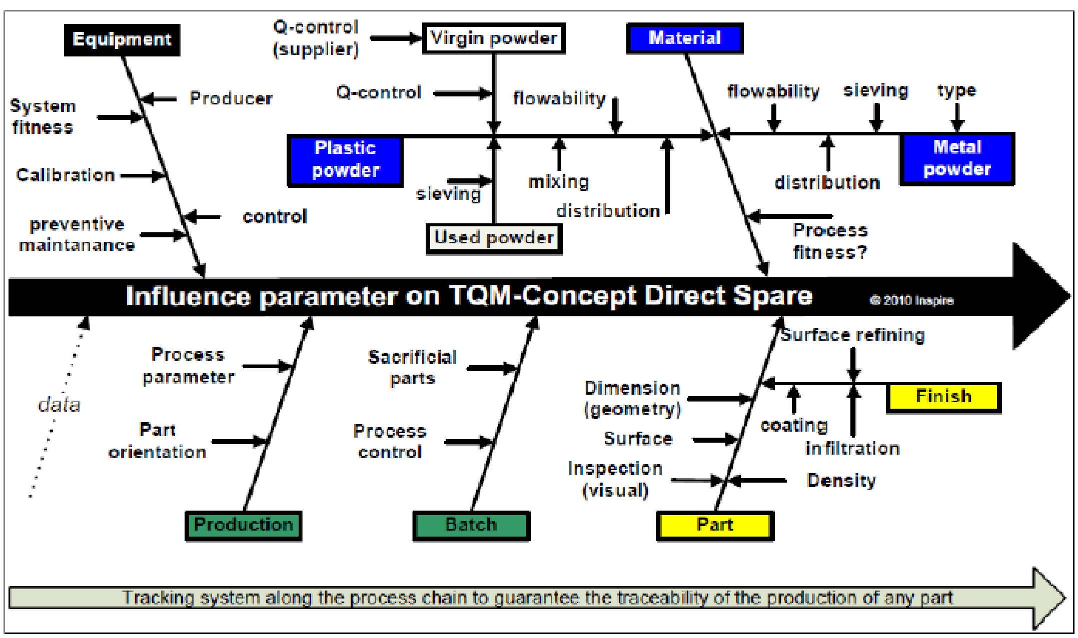
The challenges for the data management and tracking system can be summarized in two topics as follows:

1. Contribute to Total Quality Management (Traceability, Data Management, Constrain certain degrees of freedom)
2. Protect IP and prevent illegal copying (AM spare parts certificate, secure file transfer).

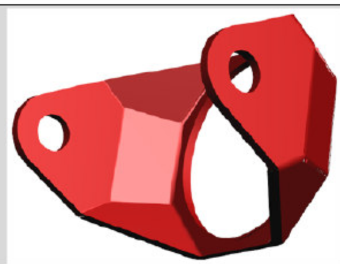
The data management and tracking software integrates the dedicated AM data preparation software. This integration is shown in the following figure:

Besides the part data integration it is equally important to set up new Q-models to achieve an interconnection of TQM to the entire business models in order to give an estimation of the costs of according Q-Actions.

Influence parameter and important aspects connected to any of these main aspects of the process chain are particularised as well and summarized in an Ishikawa diagram as an outcome of the evaluation (see Figure below).



The influencing parameters were used in DirectSpare project to set up a questionnaire with Q-relevant questions on the other hand. The information provided resulted in the development of the cost analysis tool shown below.

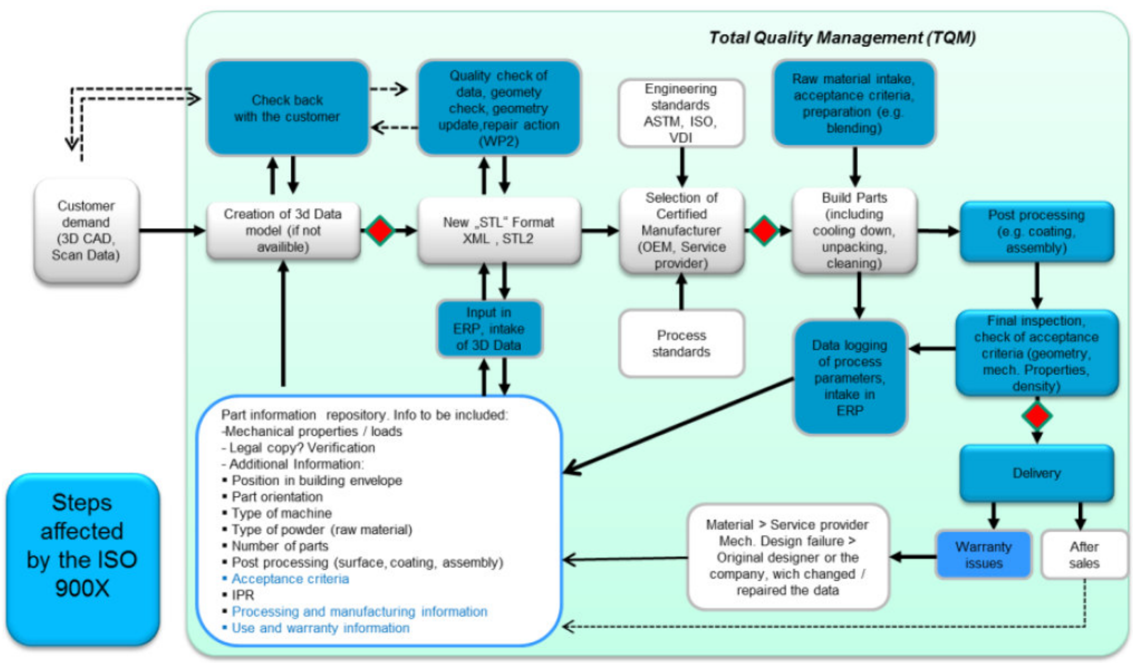


Material (current): CF/Epoxy;
Material (new): PA 12;
Dimensionen: 290 x 220 x 150 mm
Single part price (inspire): 900 €
Quantity: ca. 8 parts/job (max.)
Quantity needed: 150 total/year
Production: 20 jobs (10 weeks)
Constraint: initial material analysis; hand finishing

Gimbal (Flying Cam)	full 48 weeks production; hand finishing of parts				
	fixed costs €	flexible costs quantity	hours 50 €/h	year €	10 weeks / 20 jobs (€)
Equipment (Performance & Fitness)					
Regular performance check (maintenance contract 'regular')				35'000	7'000
Monthly Benchmark (Production&Evaluation)		12	8	4'800	1'000
Material					
Analytical Equipment (DSC, MFI)	50'000				
consumables				5'000	1'000
Material control (DSC/MFI measurements)		80 jobs	2	8'000	2'000
Production & Batch					
Build setup & process control		80 jobs	1	4'000	1'000
Part & Finish					
Final Inspection		150 parts	0.1 h		500
Post processing		150 parts	0.3 h		1'500
sum fixed costs - depreciation (10 years)	50'000			5'000	1000
Q-costs for production of Gimbal					15'000
Part price (one part)					900
Part price (150 parts with 25% discount)					101'250
Amount of Q-costs					ca. 15 %

Next to the introduction of an TQM systeme DirectSpare aims at defining new standards for RM-spare parts. The best approach will be to have a process-based standardisation system (rather than product standardisation).

In order to define and setup the appropriate standard a review of common standards across the manufacturing industry was done to determine the milestones and basic requirements. Derived from this research the following basic information was developed for the AM standard (based on the generic direct spare parts process).



As a result of the research it can be said that adopting a current standard is not a solution or an alternative to an RM standard due to the specifics of RM.

This applies as well to a certificate. A certification process for RM provides a common understanding between all involved parties when dealing with RM. A certificate can provide the following benefits:

Advantages for the customer	Advantagesfor the manufacturer / Service provider
The customer understands the standards applied (same as his)	Certification as a quality label
The customer gets products within a promised range of quality	Easier acceptance and therefore new alternative revenue streams
The expectations will be realistic (No more slogans like: AM is the one and only solution for everything)	Enabling new markets – Step into real industrial production of small and middle series
He can rely on the parts, services and processes (production and administrative) and therfore will not be disappointed at any time	Achieving higher market prices (in comparison to RP)
Parts can be handled in the „available" ERP systems (prices, postprocessing, alternative manufacturers…)	Step into new fields of applications where only certified proesses are accepted (e.g. medical, aerospace, automotive)
	Easier communication with potential customers by using common standards and terminology
	Possibility of working in supplier networks to balance the workload

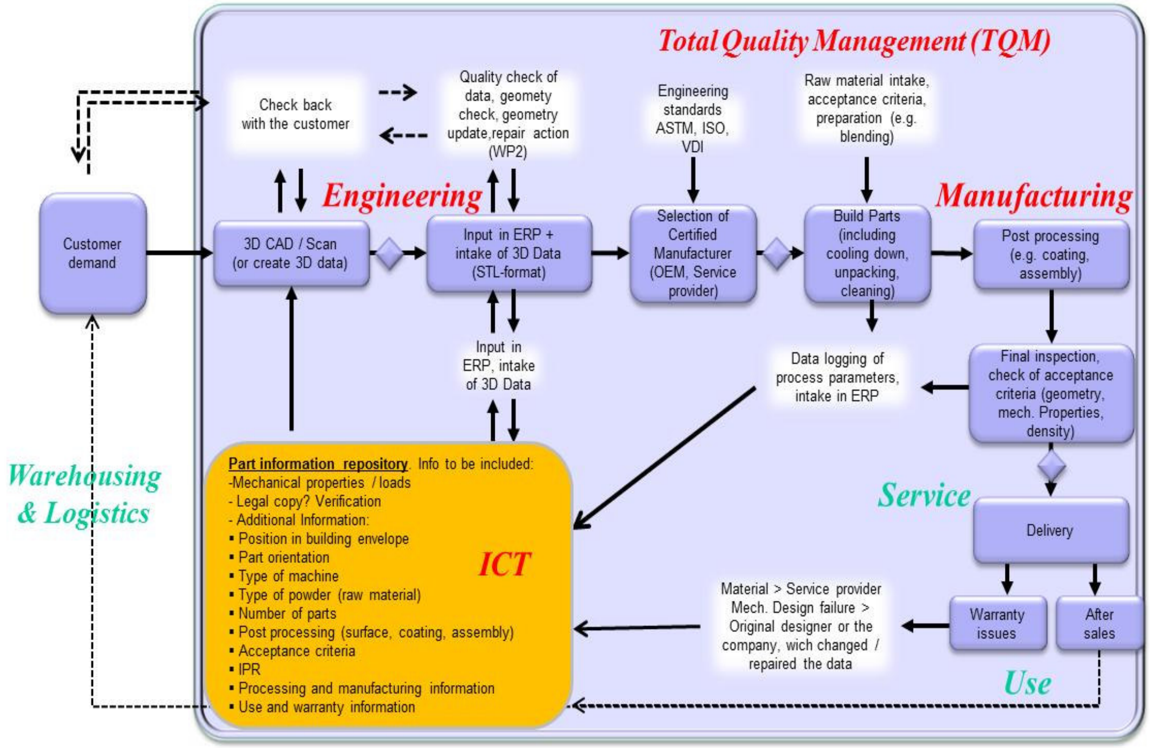
Additive Manufacturing (AM) is seen as an economically viable, enabling technology for on demand and on location manufacturing of (one-off) spare parts. Three main requirements need to be met to capitalize on the advantages of RM

1. The total costs of delivering the spare parts need to be lower than traditional;
2. The associated business model to obtain these lower costs needs to be accepted;
3. Preconditions have to be met; quality issues need to be solved
4. Standards need to be introduced.

This means however not only further research is needed but also the paradigm shifts to design a part with the intention to capitalize on benefits in the use phase.

C Potential impact, main dissemination activities and exploitation of results

In the picture below the generic Direct Spare process[2] (from customer demand to delivery) is depicted.



Even though this process model is valid and helps to overcome one of the main obstacles for acceptance of AM (namely the uncertainty of high quality output), this is not enough to expect an overnight switch to AM. We found out that introduction of AM to current value chains for spare parts without the adoption of AM-enabled business models, is cost wise not be interesting. It brings mostly additional operational costs and little additional benefits.

The increase of costs in the manufacturing phase is partially due to higher material costs and to higher labour costs (for operating machines and for finishing the part).These activities can be further automated, many initiatives are currently underway to overcome these obstacles. Manufacturing costs and in particular the additional labour costs can be lowered by full automation of processes (no more handling, setting up, cleaning, post-processing, etc.)[3].

Current material costs can however not easily be lowered. Prices for material depend on supply and demand: current demand is too small to allow for more (mass) production capacity for AM-materials and thus for lower prices. Also the current material supply structure and strict warranty regulation used by the machine suppliers limits the

[2] See report for Deliverable 5.2 of the Direct Spare project.

[3] Automation of the manufacturing process (including preparatory and finishing activities) is a topic in the research on AM as manufacturing technology. In Work Package 4 (on Manufacturing) and WP 5.4 (on Quality Management) of the Direct Spare project this topic is addressed.

possibilities of competition and price decreases. A more flexible regime would quickly lead to more demand for AM in the market, is our opinion.

Based on the three scenarios studies in Direct Spare three generic and validated business models for Direct Spare parts (AM manufactured spare parts) were developed to help companies to quickly assess the possibilities in their specific situation:

- "Balancing end of stock" for scenario 1
- "(Spare) Parts on demand" for scenario 2
- "Continuous improved (spare) parts" for scenario 3.

In paragraph 4.1 the business models will be described in more detail.

Based on these three generic business models, a simulation tool is developed with which any company could make the identification: "if my business resembles one of the scenarios, I now know which business model and supply chain setup best fits me when adopting AM".

"Balancing end of stock"

The business model for "balancing end of stock" deals with high volumes of (spare) parts, which at a certain point in time (often End of Production or End of Service; see paragraph 2.1), will all be manufactured with AM.

This business model can only be an economic viable alternative if overcoming obsolete stocks by introducing AM will result in a cost price per part that is lower than if manufactured with conventional mass manufacturing technologies. This business model applies when no conventional manufacturing facility (or mould or tools) are available anymore and the investments in traditional manufacturing tools (tooling or moulds) is high.

"(Spare) Parts on demand "

The business model for "spare parts on demand" deals with low volumes of (spare) parts, which all are manufactured with AM.

This business model can be an economic viable alternative when conventional manufacturing technologies result in a relatively high cost price per part, for instance when conventional manufacturing is labour intensive (artisan craft work) or when there is no conventional manufacturing facility (or mould or tools) available and the cost price per part with conventional manufacturing technologies will be higher due the needed investments in manufacturing tools.

On location manufacturing will increase benefits like refraining from warehousing and transportation costs. Next to this, also higher prices can be asked for shorter delivery times.

"Continuous improved (spare) parts"

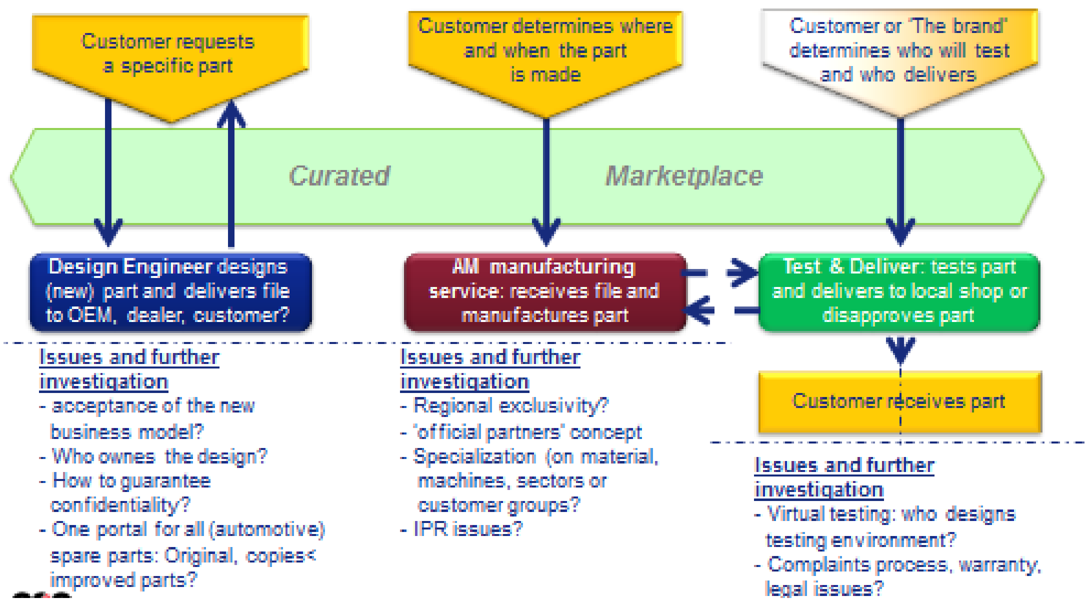
The business model for "Continuous improved (spare) parts" deals with low volumes of (spare) parts, which all are manufactured with AM.

This business model is similar to the business model "(Spare) Parts on demand". It is an economically viable alternative when a price premium can be obtained for on demand (and on location) production. A tailored setup of the value chain is required. Possible benefits from improvements in the design should be made tangible in assembly or use phases

Most interesting in this business model is the fact that improved design can lead to better individualised products, for which the customer is willing to pay a premium. The crux is the aspect of ‘willing to pay more”. In earlier projects we found out that the mere possibility of designing a better product does not immediately lead to more sales. Thus, again, it is case specific if the added engineering costs can be offset by higher margins from these improved products.

Radical changes

And again another situation would arise when a company (or multiple companies) will regard AM as the enabler for completely new business principles. For instance when establishing online (curated) marketplaces for spare part manufacturing and delivery. On this marketplace a customer could request a specific part, determine where and when and how (what manufacturing technology) the part is made, determine by whom and what standards the part is tested (quality is assured) and determine where and when an by whom the part is delivered and installed. This leads to new research questions as depicted in the picture below:



Exploitable results from Direct Spare

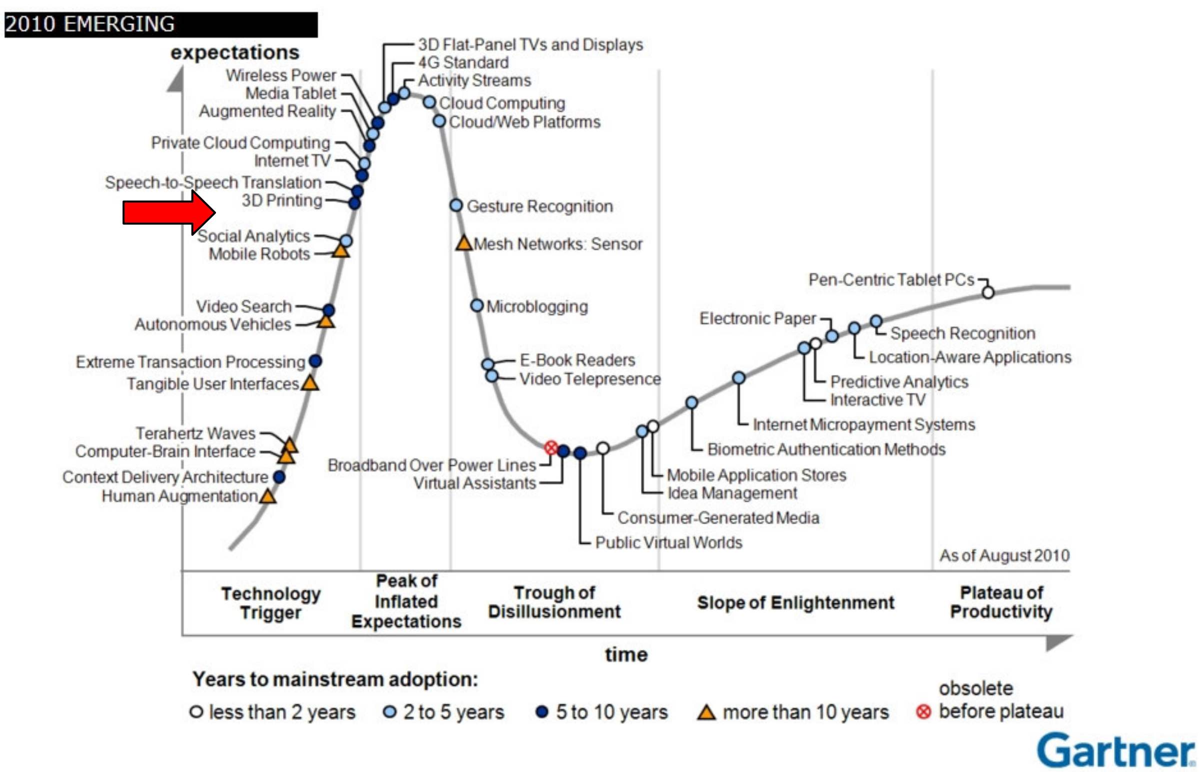
As pointed out in the figure below, the Direct Spare consortium generated results on design and simulation, materials development, process development, ICT solutions, business models and TQM.

These results are a step ahead on several barriers and R&D opportunities mentioned in this roadmap. Nevertheless, much further research is needed to fully capture the benefits AM and grow into a multi-billion market for spare parts.

	DirectSpare Sub-Results
1	Rapid design toolbox for scanning and gathering non-existing or broken parts in 3D CAD.
2	Knowledge Based System for AM technology selection (Technology Selector)
3	AM Decision Model
4	New Polymer for laser sintering
5	High performance metal for laser sintering
6	Improved laser sintering / process for aluminium
7	Design of a (modular) data management and tracking system
8	RM Spare Parts Business Model
9	RM Total Quality Management System
10	New design methodology: Copy part properties
11	Method for improvement of mechanical properties of SLS polymer parts by post processing

Roadmap for the future

AM is a rather new technology, based on rapid prototyping technologies that exist for 20-30 years now. New technologies have a tendency to go through several phases. After a huge step in technology development (technology trigger or push) expectation will rise, and only after disillusionment it will steadily grow. Gartner (2010) puts AM (here named 3D printing) in the beginning phase (technology trigger) and expects another 5-10 year until mainstream adaptation of AM is a fact.



AM is growing fast and turning into a big market, especially AM for direct part production.Still AM technologies offer several benefits for spare parts. Cost reduction (no tooling, no transport and warehousing, no assembly) especially when it concerns low volume demand of parts can be obtained. Also it can lead to a faster time to market as no tooling is needed. AM will also have many design benefits, like freedom of design, light weight parts and structures, integrated design, ergonometric design, customization, conformal cooling and insert of parts/devices, more efficient use of raw material, on location production (reducing transportation and associated carbon emissions)

However, these design benefits are not possible when the design of an already existing part can't be changed. Some benefits like customization to the body, medical scaffolds and design and print it yourself concepts a were not included in the Direct Spare scope. One aspect not mentioned above is

Conclusion

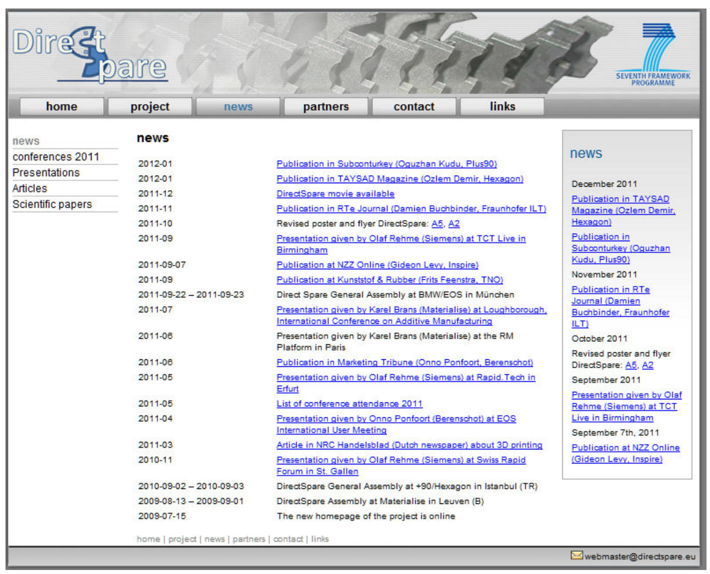
Overall the conclusion of the research indicates that AM is particularly promising when making use of the possibilities when designing new products or when adjusting parts, but to a lesser extent when trying to copy current designs to achieve cost benefits. Peter Weymarshausen of Shapeways did put it right in an interview in NRC newspaper (Netherlands, August 2011) "3D printing will become an important production technology. Not for cheap mass products, but for unique products at a reasonable price".

D Addresses, logo's and further materials

Website:
http://www.directspare.eu/index

Publications

All presentations, publications and public reports can be found on the Direct Spare website under the tab:
News



Benficiaries

All contact information can also be found on the Direct Spare website under the tab: ***Partners***

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Questionnaire http://berenschot.survey.netq.nl/nq.cfm?q=4bd4d1db-2bf0-a000-c40d-cb38a12d05f6