Universitat Politècnica de Catalunya
Departament de Projectes d'Enginyeria

Doctoral Thesis

RMADS: Development of a concurrent Rapid Manufacturing Advice System

by

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Abstract

After introducing the usual cost assesment methods for Rapid Manufacturing, anew approach is explored in this chapter aimed at the design and validation of Artificial Neural Networks for the cost-modelling of additive manufcaturing.

In this chapter two RM processes are modelled, namely Selective Laser Sintering and Selective Laser Melting. Both processes are based on the iterative deposition of thin layer of powder which are sintered (or melted) by the action of a laser beam. The chapter also makes a comparison between currently used methods and the error rates obtained by this new approach.

7. A Neural Network-based model for cost estimation based on build-time

7.1 Introduction

Cost assessment for Rapid Manufacturing (RM) is highly dependent on time estimation. Total build time dictates most indirect costs for a given part such as labour, machine costs and overheads. A number of parametric and empirical time estimators exist, however they normally account for error rates between 20-35% which are then translated to inaccurate final cost estimations.

The estimator presented herein is based on the Artificial Neural Networks ability for learning and adapting to different cases, thus the developed model is capable of providing accurate estimates regardless of machine type or model. A simulation is performed with MATLAB to compare existing approaches for cost/time estimation for a number of Rapid Manufacturing processes.

In this section the development of the ANN-based model will take Selective Laser Sintering as a sample case so that it can be contrasted against the parametric time/cost estimation methods described earlier in this chapter. The build-time information for SLS models has been extracted from the Build Setup™ v3.4 software[1] available at Fundació CIM[2] while the cost estimation model has been adapted from (Ruffo, Tuck et al. 2006; Ruffo and Hague 2007). This information is included as a spreadsheet in Annex 6.

After modelling the more appropriate model for SLS, another ANN-based model is implemented for the SLM process in order to illustrate how the same approach might be applied to different technologies/machines. Basic information on the SLM process and its usual parameters has been extracted from a number of doctoral thesis from 1996 to 2008 (Schueren 1996; Rombouts 2006; Van Elsen 2007; Van Vaerenbergh 2008) consulted during a one week research stage at Katholieke Universiteit Leuven (2008).The build-time estimation for a number of sample parts has been extracted from the software available for the CONCEPT LASER M3 SLM machine installed in the Mechanical Engineering Lab at the K.U. Leuven[3].

While error rates observed for the ANN-based model for SLS range from 2 to 15%, the ANN models implemented for SLM range between 5 and 7% which shows the validity and robustness of the proposed method.

7.2 Previous applications of ANNs for estimation

Artificial Neural Networks (ANNs) have been already applied to different aspects of manufacturing such as production planning, management and simulation. Venugopal and Narendan (1992) modelled a Design case retrieval system by using a Hopfield network. The use of ANN for design data retrieval was also studied by Kamarthi et al., (1990). Instead of Hopfield networks, a back-propagation network was used. Smith, German et al. (2002) conducted their research so as to apply artificial intelligence to the problem of material selection. They trained a backpropagation neural network with experimental data for ferrous P/M data achieving reductions on the standard deviation of the effectiveness errors around 36% when compared to other statistical methods. Huang and Zhang (1994) provide an exhaustive compilation of previous ANN applications in different manufacturing domains such as design, process planning, production scheduling, control, quality assurance and robotics. However few works have been so far devoted to assessing cost estimation with Neural Networks.

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[1] 3D Systems Build Set Up software http://www.3dsystems.com/products/software/index.asp

[2] Fundació CIM-UPC Centre Tecnologic. Barcelona Spain

[3] K.U. Leuven http://www.kuleuven.ac.be/ Leuven, Belgium

Wang and Stockton (2001) showed the benefits of applying ANNs to the cost modelling process by depicting the appropriate "cost estimating relationships" (CER). They applied the Taguchi method to determine the number of experiments to select the appropriate ANN for the case of aerospace industry. Chen (2002) studied the implications of the use of ANNs for early cost estimation, applying a backpropagaton neural network to a case study of a strip steel coiler. Their comparative study reveals that the proposed system outperforms traditional linear regression analysis models using a training sample of 18 elements and other 4 for validation. Gerrard et.al (1994) reported 20 samples of pressure vessel cost as a function of the height, diameter and wall thickness obtained directly from a manufacturer. Although the authors claimed that the neural network approach outperformed the regression approach, the conclusion was based on the "resubstitution method" where the construction sample is identical to the validation sample. Another example of the comparison between regressions and ANNs for cost estimation based on a small sample set was introduced by Brass et.al (1994), using pipe cost data for a sample set of 16 units and constructing a neural network model with 10 training samples and 6 for validations. The authors observed better results in the latter case.

Smith and Mason (1997) examined the performance & stability of cost estimation modelling using regression versus ANNs. Results show the advantage of using ANN's for handling data that doesn't fit low order polynomials.

The applicability of neural networks for cost estimation in early phases of product design was also studied by Bode (2000) where a number of distinct ANN configurations were tested including different training set sizes (10, 20, 100) and interconnection nodes. A Back propagation algorithm was implemented obtaining relative deviations from 9 to 32% lower compared to other methods such as linear and non-linear regression. Also Cavalieri et al. (2004) designed a number of multilayer perceptron ANNs in order to test their functionality against parametric systems for cost estimation in the foundry industry. Through the use of two performance indicators namely: mean absolute percentage and Generalisation factor, the level of error provided by ANNs ranged from 5 to 10%, while conventional parametric methods showed a maximum of 15%.

Although a number of ANN settings must be made by trial and error, such as choosing the number of inputs, neurons and layers, ANNs are considered a feasible and promising tool for estimation purposes. ANNs are non-parametric estimators i.e. they attempt to fit curves through data without being provided a predetermined function with free parameters (Bode, 2000) therefore they are able to detect hidden functional relationships between product attributes and cost that in some cases are unknown to the cost engineer.

This work aims to design an ANN model to provide an accurate time estimation method for different RM technologies which consequently allows for rapid and precise evaluation of cost and its relationship with the parameters selected as input. Since most of the existing parametric models are devoted to the SLS process (Ruffo, 2006b; Wilson, 2006; Phillipson, 1997), the ANN model designed in this research will also be applied to SLS. Results will be compared with previous parametric models so as to ensure the feasibility of using the proposed method to be applied to different RM processes.

7.3 Experimental procedure. An application to Selective Laser Sintering (SLS) and Selective Laser Melting (SLM)

7.3.1 Experimental data

Selective Laser Sintering and its derivate technologies are based on the deposition of powdered material such as nylon, elastomer, metal, etc. that is deposited on the workspace by means of a levelling roller. The laser controlled by a scanning device selectively melts the model cross-section for each iteration. After the sintering phase is completed the elevator moves up one layer thickness and the build chamber lowers the same distance, to start the powder deposition again until the part is complete (Figure 7. 1).

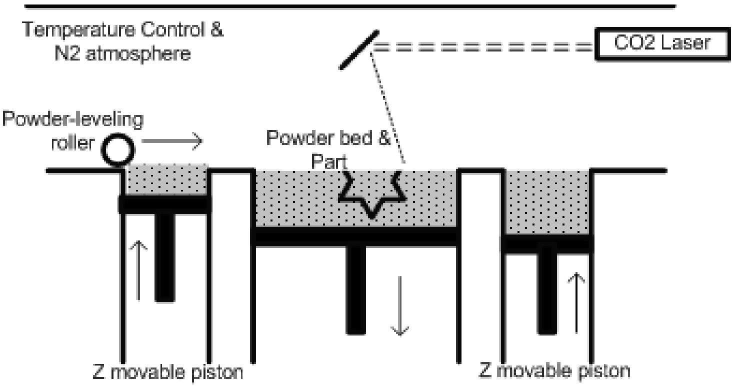


Figure 7. 1 Schematic representation of the SLS process

While there are a number of process parameters with a direct influence on the final results, there are some others whose effect on the final part remains unclear. Schaub et al. (1997) classified RP parameters into nuisance, constant and control parameters. Nuisance parameters are defined by Choi and Zamavedam (2002) as those which are not controlled during the experimental analysis but may have some effect on a part.

These include laser age, beam accuracy, humidity level as well as the accuracy expected from moving mechanical parts. Constant parameters are those pre-defined by the machine type such as beam diameter, laser focus, scan speed or those regarding material properties. The last type includes all those user-defined parameters that affect directly the build results: layer thickness, hatch space, scan pattern, part orientation, etc. Other parameters are related to the powder used, such as the grain size or the relative proportions of the components(Boillat, Kolosov et al. 2004).

Although the additive fabrication principle is the same for SLM there are some basic features that may be highlighted. SLM requires the design and calculation of support structures which guides to major material usage (and waste) besides and extra time for material removal and part finishing. Also there are a number of different factors that affect the process such as: molecular mass, viscosity, and thermal conductivity of the metallic powder. Regarding the machine itself some factor such as build-chamber pressure, oxygen level and ambient temp must be considered. Figure 7.2 and 6.3 illustrate the SLM process and its internal sub-processes.

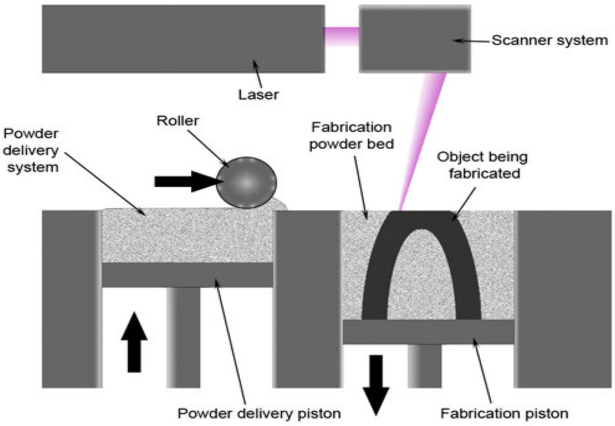


Figure 7. 2 Schematic representation of the SLM process

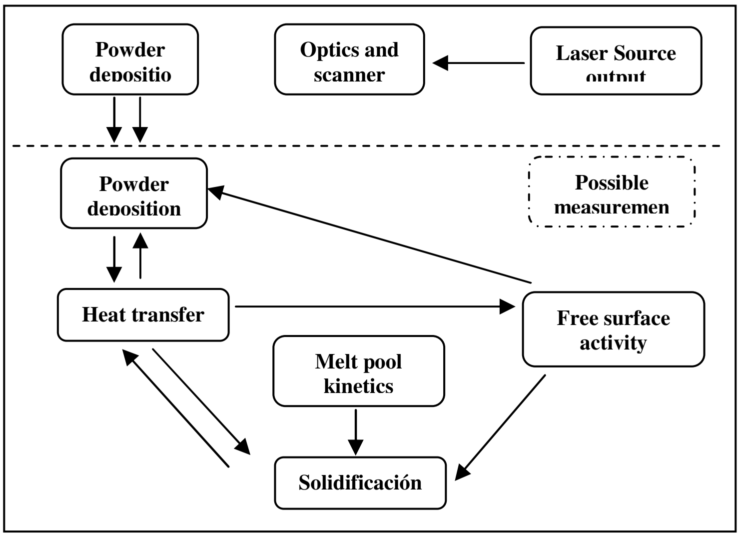


Figure 7. 3 SLM sub-processes and their interactions

In order to make a fair comparison between different time estimators, the ANN-based model must be designed under the same build conditions. More specifically, the time estimator developed by Ruffo (2006b) was designed for a 3D systems Vanguard SLS machine, thus the same machine considerations are adopted for the model proposed herein. Time estimations for the sample parts were obtained from the Build Setup^{TM} v3.4 software using the default settings with Duraform PA as selected material. Table 7.1 depicts the values used to obtain the final build times for the training and sample sets.

Table 7. 1 Default SLS process parameters used to obtain build time estimates. Usual settings at Fundació CIM

Parameter	Value
Wam-up height	12.7 mm
Cool-down height	2.54 mm
Layer thickness	0.1 mm
Laser power	42 W
Outline laser power	5 W
Fill scan spacing	0.3 mm
Bed temperature	130 ^{o}C

On the other hand for the SLM build-time estimation model, there's no parametric counterpart for comparison, therefore the build parameters usually applied at the Katholieke Universiteit Leuven lab, will be used as standard as shown in Table 7.2.

Table 7. 2 Default SLM process parameters used to obtain build time estimates on the Concept L3 SLM machine software

Parameter	Value
Laser speed	380 mm/s
Laser focus diameter	0.18mm
Laser power	95W
Hatch spacing	140 µm
Layer thickness	30 µm
Energy density	119 J/mm^3

As additional information, the previous parameters allow for a final part density of 95.11% which means the most stable and constant setting-up of the parameters. Another special requirement for the SLM process is an almost inert atmosphere, for Stainless steel the gas used is N_2 while for Titanium and its alloys it uses Argon. For both cases the oxygen level should not exceed 0.3% that is to assure the integrity of the materials due to the extreme dependence on the processing environment.

7.3.2 Neural Network modelling

Artificial neural networks have been defined by Rumelhart (1989) as *"massively parallel interconnected networks of simple (usually adaptive) elements and their hierarchical organizations which are intended to interact with the objects of the real world in the same way as biological nervous system"*.

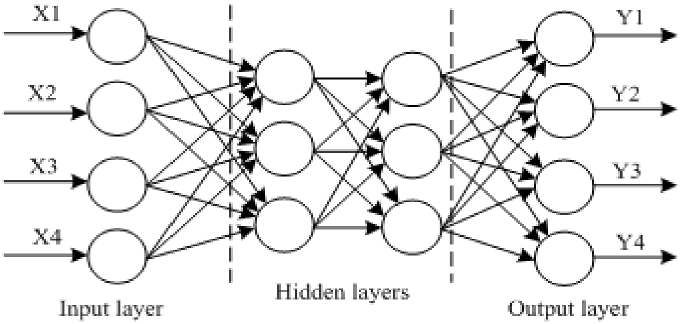


Figure 7. 4 A typical Artificial Neural Network structure

Artificial Neural Networks are inspired in the human brain functionality and structure, which can be represented as a network of densely interconnected elements called neurons (Figure 7.4). The basic components of a neural network are nodes (neurons) and weights (connections). Connections between neurons are called synapses; they can have different levels of electrical conductivity, referred to as the weight of the connection (2004). Positive weight represents an excitatory connection while a negative weight represents an inhibitory connection. Through this array knowledge is stored. According to its architecture, the network will respond to different inputs in different ways according to the stored weights, hence activating a different output neuron that generates the ANN result.

An ANN is characterized by its ability to learn and make inferences based on input data. In order to learn, it must be trained which means that a set of training data will be taught (stored) in a selected architecture. Once learning is achieved, the ANN may have the capacity to infer about previously unseen data inputs, which is called “generalization” capability.

Basically there are two main types of ANNs: feed-forward networks and recurrent networks, however they can also be classified in terms of the guidance received during the learning process into: supervised and unsupervised (Huang, 1994). Unsupervised learning networks learn to classify the input into sets without being told anything. Supervised *learning* networks adjust their weights on the basis of the difference between the values of output units and the desired values given as “target”.

7.4 ANN-based time estimator development

As mentioned earlier in this chapter the purpose of using ANNs is to address time estimation for SLS and SLM. Once the final time estimate is obtained the cost approximation is performed by using a parametric costing model which considers direct costs, labour costs and overheads.

The methodology used in order to assure the repeatability of the model for being applied to different RM processes is based on the following phases:

1. Definition of the main build-time drivers
2. Database compilation
3. ANN Design
4. Evaluate ANN

7.4.1 Definition of the main drivers

The aim of the study is to find the right inputs for the model, i.e. those with the highest impact on the estimated build time. According to existing parametric time-estimation models, input data should correspond to simple geometrical variables. It normally comprises from 3 to 5 parameters. Early studies on RP build-time estimation were based on the total scan length and laser speed (Kamash, 1995), while more recent models calculate time as a function of part volume, height and surface area (Phillipson, 1997) or considering also the part bounding-box volume (Ruffo, 2006b; Wilson, 2006).

In order to identify the most useful input parameters for SLS and its derivate technologies, a series of correlation analysis were performed for a number of attributes as shown in Figure 7.5. From this analysis three input parameters were selected: z height, part volume, and bounding box volume. Although the latter shows a low correlation it can provide useful hints to the ANN since the relation between build volume and part volume is usually considered a measure of part complexity.

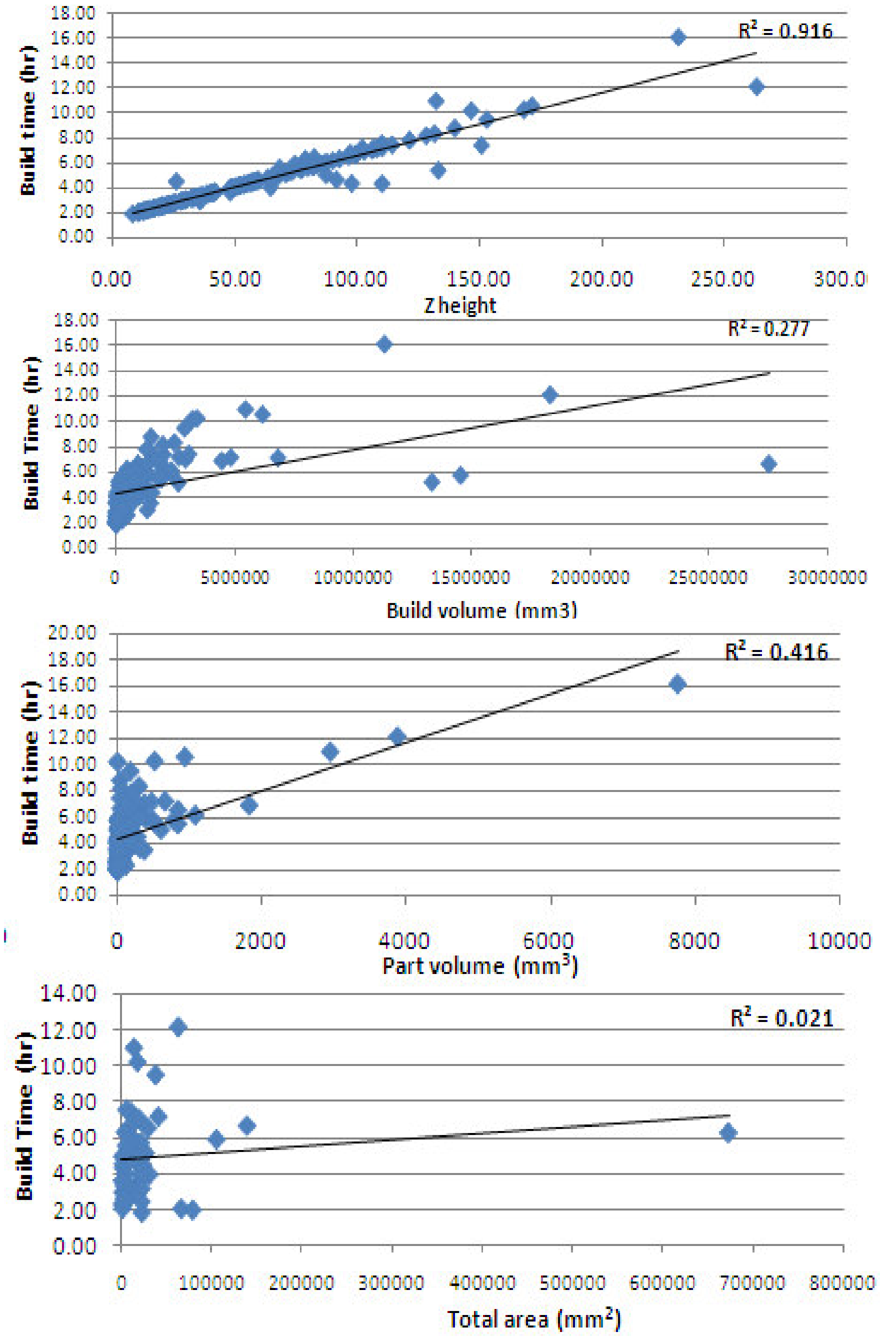


Figure 7. 5 Correlation analysis for potential input parameters against final build time based on 130 samples. (SLS)

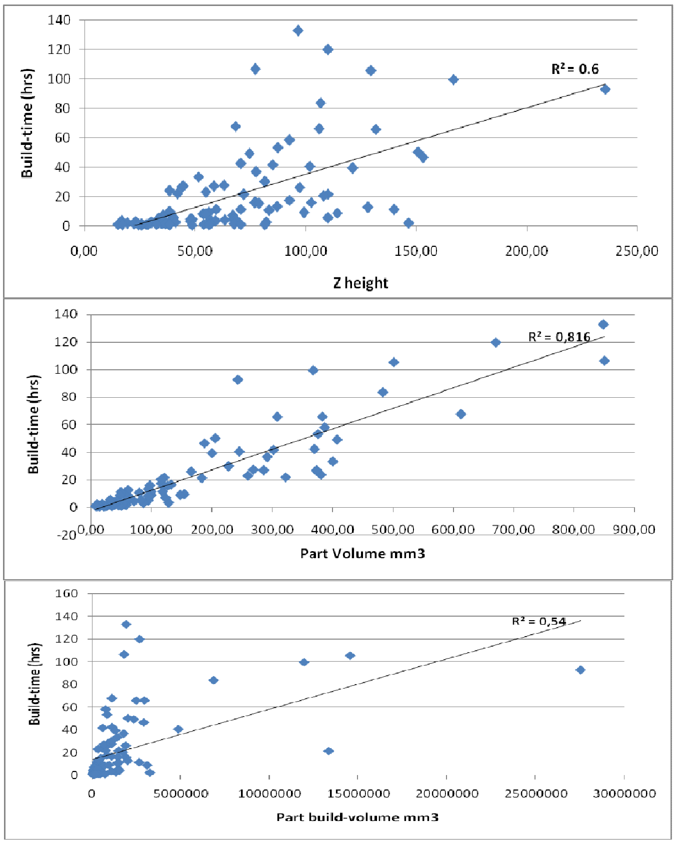


Figure 7. 6 Correlation analysis for potential input parameters against final build time based on 130 samples (SLM)

7.4.2 Database compilation

In order to compile a sufficient case base, a data set with the parameters selected in section 3.1 is utilized to design the ANN model. A collection of 130 models (Annex 4) has been used to train and simulate the different ANN architectures designed during the research. From this data, 90 samples were used for training, 25 for validation and 15 for performance testing. All data has been normalized to the (0, 1) interval and trained in a batch mode. Experimentation has been carried out using MATLAB Neural Network Toolbox (Mathworks 2006).

7.4.3 ANN Design

Once the database with 130 cases was compiled it was necessary to perform a data integrity check. It was done by means of a simple Ms Excel spreadsheet in order to find missing data, or inappropriate data ranges. Since the success of the ANN model depends on data quality, only those parameters with a direct influence on the final result will be chosen, thus eliminating potential sources of noise in the model (Huang, 1994).

The architecture of a multilayer perceptron network must be carefully designed, since the number of nodes will define whether the ANN selects a complex or a simpler function to approximate data as shown in Figure 7.4. Usually, a higher precision brings along poorer generalization capabilities for an ANN however there are not currently formal rules for the selection and design of ANN topologies. This remains as a quite experimental task which some times is based on trial and error therefore it is not possible to predict development time with sufficient accuracy.

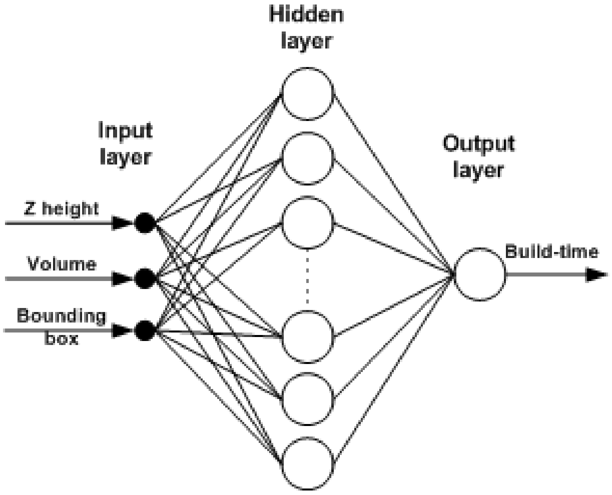
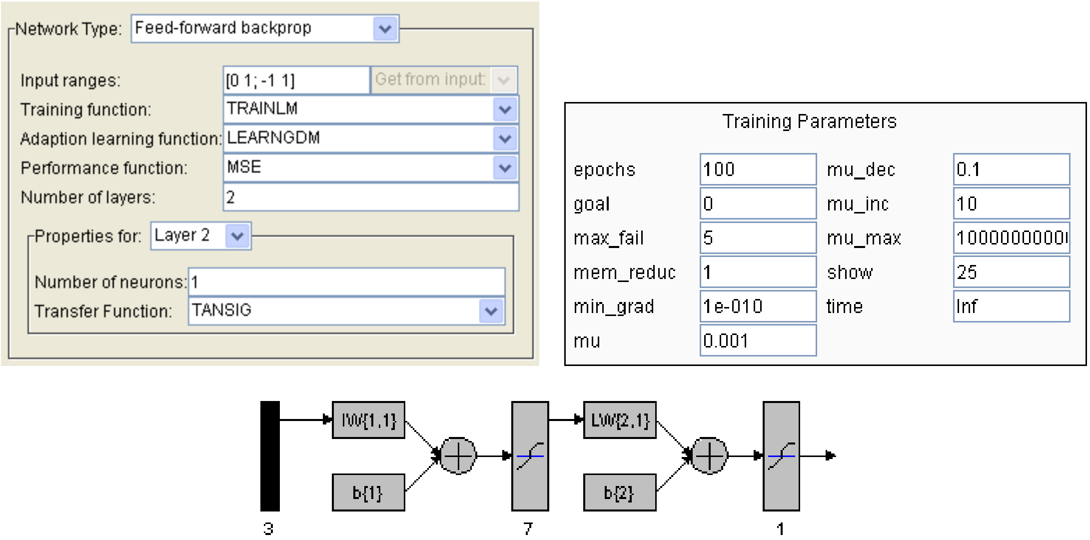


Figure 7. 7 ANN architecture selected for the model

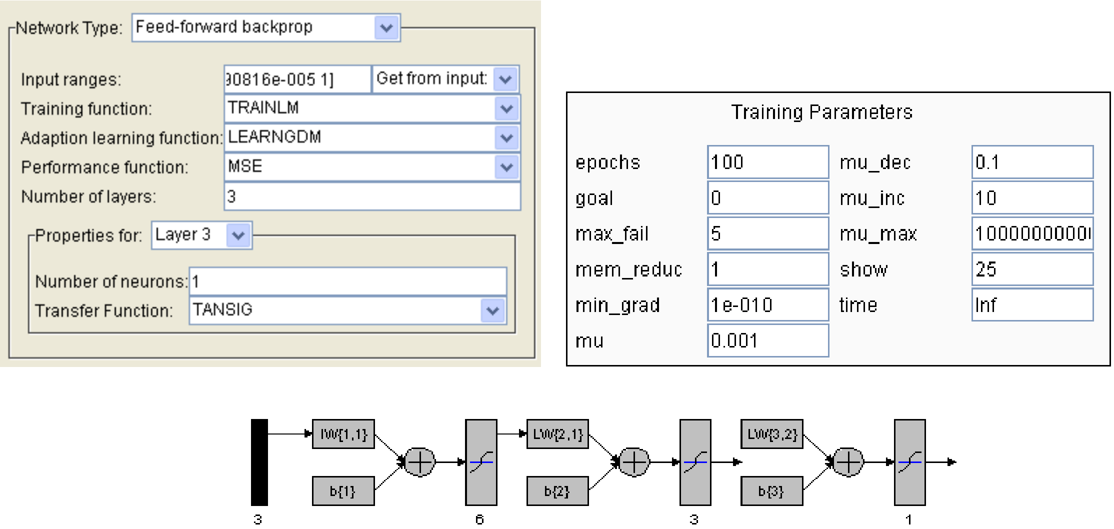
As defined previously a Multilayer perceptron architecture has been selected for these models. It is assumed that since the same principle of additive fabrication of SLS is used for SLM the selection of the neural network architecture should be alike. The learning algorithm adopted is the Levenberg-Marquardt since it has been shown that it is often a more efficient alternative to steepest ascent algorithm and its variations and also it is faster in converging (Haykin, 1999). A topology of 3 input nodes and one output node has been adopted, however in order to define the best performance, different configurations from 1 to 3 hidden layers were tested. Figures 6.8 and 6.9 show the design of two sample ANN models on the MatLab Neural Network toolbox along with the algorithm selection and training criteria.


Network Type: Feed-forward backprop
Input ranges: [0 1; -1 1]
Training function: TRAINLM
Adaption learning function: LEARNGDM
Performance function: MSE
Number of layers: 2
Properties for: Layer 2
Number of neurons: 1
Transfer Function: TANSIG

Training Parameters

epochs	100	mu_dec	0.1
goal	0	mu_inc	10
max_fail	5	mu_max	1000000000
mem_reduc	1	show	25
min_grad	1e-010	time	Inf
mu	0.001		

Figure 7. 8 Selection of the ANN parameters and training configuration for the SLS model



Network Type: Feed-forward backprop

Input ranges: 90816e-005 1] Get from input:

Training function: TRAINLM

Adaption learning function: LEARNGDM

Performance function: MSE

Number of layers: 3

Properties for: Layer 3

Number of neurons: 1

Transfer Function: TANSIG

Training Parameters

epochs	100	mu_dec	0.1
goal	0	mu_inc	10
max_fail	5	mu_max	1000000000
mem_reduc	1	show	25
min_grad	1e-010	time	Inf
mu	0.001		

Figure 7. 9 Selection of the ANN parameters and training configuration for the SLM model

The reader can also refer to the Matlab codification of the networks located in Annex 7 where the training parameters and NN configuration are defined.

```
Line 2738%=== Code for generating the SLS ANN
net= newff([0.017709772 1;0 1;2.90816e-005 1],[7 1],
{'tansig' 'tansig'}, 'trainlm','learngdm','mse');
Mired_SLS = init(net);
net1 = train(Mired_SLS,p,t);
Line 2687 %=== Code for generating the SLM ANN
net_2= newff([0.064762876   1; 0.008737065  1; 0.00172886 1],[6 3 1], {'tansig' 'tansig' 'tansig'},
'trainlm','learngdm','mse');
Mired_SLM_1 = init(net_2);
net_M1 = train(Mired_SLM_1,p,t);
```

7.4.4 Evaluate ANNs

In order to verify the ANNs capability to be used as an estimating method a number of performance measures have been applied, namely the percentage of correct classifications (Bode, 2000; Cavalieri et al.,2004) and the deviation of estimated values from target results in percent. The mean absolute percentage error is defined as:

$$\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\left|Estimated \quad \cos t_i - Actual \quad \cos t_i\right|}{Estimated \quad Cost_i}100\right) \qquad (1)$$

While the Generalization factor is defined as:

$$Gf = \frac{k}{n}100 \qquad (2)$$

Where *n* is the sample set used for validation and k are the estimations with error less than 5%. Smith and Mason (1997) discussed the presence of the “resubstitution method” in several papers that addressed the validation of the performance of ANN models. That is, the use of non-independent simulation samples that artificially improve the overall performance of the network but that induce significant and not acceptable bias on the final results. In order to prevent this, an independent sample has been used as a simulation set. The reader may notice that results presented in Tables 6.3 attest the use of independent data. While the training sample set shows error rates below 5%, simulation set error tends to show a bigger value which seems to be related to the generalization factor of the network.

Table 7. 3 Performance comparison for different ANN architectures (SLS)
Note: The best performance configurations are highlighted in yellow

Hidden layers				% Training set error	% Simulation set error	Generalization factor
	Layer 1	Layer 2	Layer 3			
1	3	0	0	5.070	13.342	73%
2	5	0	0	5.126	21.467	69%
3	7	0	0	4.362	14.893	83%
4	3	5	0	4.695	16.469	71%
5	5	3	0	5.348	12.498	63%
6	5	4	0	4.637	33.832	71%
7	6	3	0	4.814	18.294	65%
8	8	4	0	5.462	11.874	69%
9	10	4	0	150.062	85.651	4%
10	12	4	0	3.299	711.317	71%
11	15	3	0	4.775	71.103	71%
12	3	6	3	4.676	17.204	69%

From the analysis shown in Table 7.3, ANNs 1 and 3 seem to be the most effective architectures to describe the SLS time calculation, however when different training and validation samples are used, the final performance might also change therefore a sensibility analysis between the two best architectures has been performed, by varying the training set sizes (Figure 7.10).

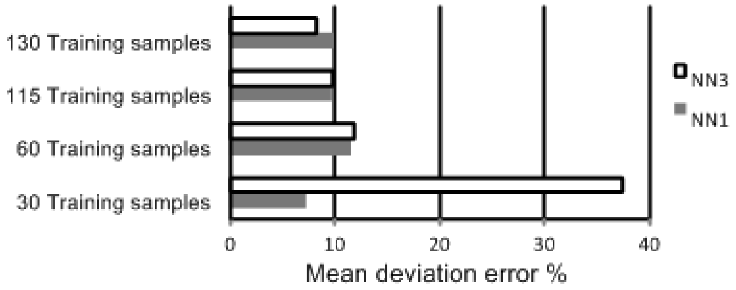


Figure 7.10 The effect of training sample size on the 2 selected ANNs

For statistical repeatability several training sets of equal size were chosen for experimentation. It was observed that as the number of training samples is increased, the relative deviation percentage consequently decreased. However, when a relatively optimum error level is achieved, the more training samples are added, the smaller the increase on performance.

Figure 7.10 also shows that the training set size has little effect on the final mean deviation error. Moreover hidden layer size has a low impact on the ANN performance between the two architectures compared. However, since NN3 trained with 130 samples has a greater generalization factor, it will be used as the optimum model to compete against parametric estimators.

Table 7. 4 Performance comparison for different ANN architectures (SLM)
Note: The best performance configurations are highlighted in yellow

	Hidden layers			**% Training set error**	**% Simulation set error**	**Generalization factor %**
	Layer 1	Layer 2	Layer 3			
1	3	0	0	4.540	25.619	71.5%
2	5	0	0	4.570	26.724	71.7%
3	7	0	0	4.370	39.152	70%
4	3	5	0	4.360	48.633	65%
5	5	3	0	8.558	6.962	80
6	5	4	0	1.509	3.795	70
7	6	3	0	1.815	2.549	80
8	8	4	0	2.228	3.623	67
9	10	4	0	52.090	59.040	0%
10	12	4	0	213.850	353.969	0%
11	15	3	0	73.650	82.798	0%
12	3	6	3	-	-	-

Regarding the SLM process, no sensibility analysis has been performed since from the results in Table 7.4, the configuration 6-3-0 shows a priori a better performance. The selection of the different ANN architectures to be testes follows the criteria adopted by (Cavalieri 2004) to iteratively increase the complexity of the ANN until results show no further improvement. It can be seen how the middle ANN architectures show accurate enough results while an increase in the number of nodes guides to unreliable results. One explanation is that as the mechanism of time calculation followed by the SLS equipment is similar as that from SLM, the differences in the processing parameters as described in Table 7.1 and 6.2, guide to a relatively slight change on the ANN model appropriateness. There’s no wonder why the ANN models that describe both processes as shown in this research, are not that dissimilar.

Besides applying the previous methods for performance verification there are other strategies that may be applied for reducing the overall marginal error that results from the use of ANNs for estimation. One method tested during this work is the integration of ANNs with other Artificial Intelligence techniques such as Case Based Reasoning. As the effectiveness of ANNs relies on having a sufficient case-base in order to correlate geometrical features acquired during training to the geometrical features presented by new cases, it is fair to assume that only those cases stored in the database with a sufficient level of similarity might contribute to a reliable estimation. Therefore it is possible to apply strategies such as the “Degree of Similarity” (Muller and Selk 2003) as shown in equation 3.

$$sim[a_n;b_n] = 1 - \frac{|a_n - b_n|}{a_n + b_n} \tag{3}$$

Where:
a_n : value for attribute n in case a
b_n : value for attribute n in case b
sim : degree of similarity between the two cases a and b regarding the attribute n
Once the numerical attributes are covered, the overall degree of similarity is determined using the following formula:

$$DS = \frac{\sum_{i=1}^{n} W_n * sim[a_n; b_n]}{\sum_{i=1}^{n} W_n} \tag{4}$$

Where:
W : A given Weighting factor for the n feature
DS : Overall degree of similarity
By following this approach only those cases within a pre-determined range would be suitable to be included as training samples for the network, hence reducing sources of noise and eliminating the generalization capabilities that are not necessary.

7.5 Comparison of ANN results vs. parametric build-time estimators

Since there exist only parametric build-time estimators for SLS and not for SLM, this section is devoted to the SLS network compared to those systems available. According the previous results an ANN configuration of 3 input parameters, one hidden layer with 7 hidden nodes and 1 output node seems to be the most appropriate architecture to be used for further comparison. In order to speed up the simulation of the 2 benchmarked methods(Ruffo, Tuck et al. 2006; Wilson 2006), their formulae and calculations were implemented as MATLAB functions (see Annex 3). A detailed description and illustration of the methods was shown in the previous chapter, or can be found in (Ruffo, 2006; Wilson 2006).
Table 7.5 shows a sample of 15 parts with the corresponding information, actual build-time and the estimation provided by the methods studied.

7.6 Results and discussion

Build-time values predicted by Artificial Neural Networks show a marginal error constantly lower than 10% while the other compared methods exhibit more variable results that can reach 30-35% of error for some sample parts (Figure 7.11). The reason of such variability may be explained as a failure of the parametric model to “understand” and capture the real context being used to construct a given part. The model developed by Wilson makes use of specific SLS process parameters such as: laser beam diameter, scan speed, laser jump speed, draws delay, etc. which intend an accurate estimation, however if any of those parameters is unknown the model may respond with very high or unreal time estimations. Although the model developed by Ruffo makes an accurate enough estimation, it cannot be applied to any other RM process or even a different SLS machine since it was obtained by curve fitting the SLS system responses for a pre-established set of parameter conditions.

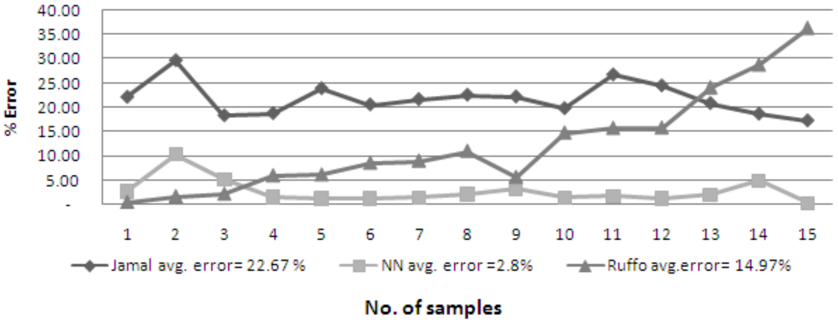


Figure 7. 11 Percentage of estimation error compared among the 3 methods.

Part No	Height (mm)	Volume (cm^3)	Bounding box (mm^3)	Actual Build time (hr)	ANN time est.	% Error	Wilson time est.	% Error	Ruffo time est.	% Error
1	29.79	54.4	109942.8	**2.98**	2.906	0.22	3.83	22.13	2.9677	0.5
2	54.93	94.22	684636.4	**4.3**	4.391	1.99	5.437	20.83	5.6697	24.09
3	66.88	64.79	144372.9	**4.93**	4.695	5.1	6.039	18.3	5.0444	2.19
4	17.02	34.3	60826.13	**2.32**	2.288	1.24	3.045	23.93	2.182	6.15
5	16.71	128.13	262497.7	**2.32**	2.28	1.58	3.163	26.79	2.7479	15.73
6	59.16	36.53	1096991.	**4.54**	4.767	4.8	5.577	18.62	6.3677	28.72
7	35.71	5.56	16931.08	**2.89**	3.219	10.2	4.115	29.76	2.9401	1.68
8	21.35	10.44	46159.45	**2.54**	2.488	2.03	3.279	22.58	2.2864	11.02
9	152.9	187.59	2916396.	**9.49**	9.511	0.25	11.46	17.24	14.891	36.29
10	48.1	39.59	536775.7	**3.95**	4.009	1.36	4.928	19.77	4.6398	14.78
11	48.52	9.71	76958.28	**3.97**	3.907	1.53	4.882	18.75	3.7429	5.98
12	36.57	27.96	303849.4	**3.35**	3.314	1.16	4.221	20.56	3.6685	8.6
13	39.84	70.81	256691.6	**3.51**	3.466	1.35	4.484	21.66	3.861	9.01
14	12.21	6.13	21242.02	**2.06**	2.086	1.16	2.731	24.5	1.7802	15.81
15	150.8	205.31	2032952.	**7.4**	8.043	8.02	11.33	34.76	13.241	44.13
					Avg.% Error	**2.8**		**22.68**		**14.98**

Table 7. 5 Sample parts simulated with parametric and ANN based models

The neural networks approach shows a better fit to the given set of case examples. Although the relationship between the internal SLS process parameters remains unknown it may be an appropriate strategy for applying similar models to other RM processes where the exact cause and effect of every parameter is not yet well defined but there's a need for reliable time or cost estimation. As shown in Table 7.6 the difference on the parameters used by a parametric and a ANN-based approach is notable.

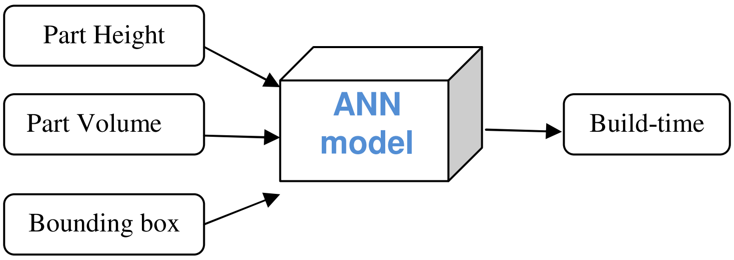


Figure 7. 12 Parameters considered for the ANN based models

Table 7. 6 Parameters usually considered for parametric time-estimation methods (27 parameters)

Machine parameters:	**Material Characteristics**
length of RP vat (x-direction) (mm)	material density (g/cm3)
height of RP vat (z-direction) (mm)	material cost per mass ($/kg)
width of RP vat (y-direction) (mm)	
useful life of machine (yrs)	
Material Deposition parameters:	**Scan profile parameters:**
scan (draw) diameter (length)	number of times the given surface is scanned (drawn) for parts
percentage overlap of scans (%)	number of time the given surface is scanned (drawn) for supports
jump velocity (mm/s)	factor used to account for inclusion of supports (%)
scan (draw) velocity (mm/s)	minimum height of supports (mm)
layer thickness (mm)	
Machine Time parameters: (1)	**Machine Time parameters: (2)**
pre-processing technician (hrs)	time for material sweep
post processing technician (hrs)	delay between material sweep and draw
delay after draw,	total time for scanning (drawing) part (s)
time for stage to move down	machine warm-up/setup time (s)
delay time between stage movements	time for material deposition sweep (s)
time for stage to move up	total time between scans (s)

Unfortunately there is not a parametric build-time calculation method for SLM developed in previous research. There are though, many proprietary methods for time estimation developed by machine owners however this information is not disclosed as it comprises a source of price competitiveness and therefore a commercial advantage. There's however a relatively standard estimation error of between 15-25% that is assumed by using these methods (Van Vaerenbergh 2008). For the SLM process time estimation may not be the definitive costing factor as there are other elements of cost inherent to metal treatment such as post-processing and finishing that may account for as much as 85% of the final selling cost. A remarkable fact may be that the same strategy for ANN design for the SLM can be extrapolated to a number of different technologies, as the "Selective Laser Melting" is a "trade name" that differs from other process names due to intellectual property rights. Table 7.7 shows some of these technology variations and their respective manufacturer.

Table 7. 7 Manufacturers of different technologies based on SLS/SLM

Manufacturer/ Technology name	Manufacturer data
Trumpf laser technology	http://www.trumpf.com/
Concept Laser (Laser Cusing)	http://www.concept-laser.de/
MTT (Laser melting)	http://www.mtt-group.com/
EOS (Direct Metal Laser Sintering)	http://www.eos.info/
Phenix systems (Laser Sintering)	www.phenix-systems.com

7.7 Implementing the Cost estimation routines based on build-time

For the purpose of this Thesis the calculation of costs is performed by matching the build-time estimation provided by Artificial neural networks and the costing spreadsheets introduced by Ruffo et al. (2006). Data regarding material costs, machine average life, labour costs and overheads has been obtained from a number of specialized sources (Wohlers 2006; Hopkinson 2006; Ruffo, Tuck et al. 2006; Wilson 2006; Ruffo and Hague 2007; Munguia, de Ciurana et al. 2008). The complete costing datasheets can be consulted in Annex 6 for further information.

Table 7.8 shows the parameters considered for the costing model which include a detailed number of sources of indirect cost obtained from the literature listed above. Other parameters however such as the "machine uptime" which refers to the percentage of time that the machine is up and working, has been obtained by estimates that show the difficulty of increasing the utilization of a RM over 60 per cent (ManRM 2006).

Table 7. 8 Parameters obtained from users and commercial information

Indirect costs	***Machine costs***
Production overhead	**Machine & breakout station purchase**
Yearly rent rate (per m2)	**Purchase cost/year***
Building area (m2)	**Maintenance/year**
Energy consumption/h	**Software purchase**
	Hardware purchase
Administration overhead	**Software cost/year***
Hardware purchase	**Cost of software upgrades/year**
Software purchase	**Hardware cost/year***
Hardware cost/year*	**Depreciation period for computer hardware**
Software cost/year*	**Machine depreciation**
Consumables per year	
	Machine Uptime (%)
Production labour	
Technician annual salary + employer contributions	

Table 7. 9 Parameters calculated by formulae for Cost allocation

MATERIAL EQUATIONS	
Waste factor	α E [0,1]
Material waste	$W_B=(V_{beds}-V_B)*\alpha$
Material used	$m_B = \rho * (V_B + W_B)$
Volume of different build beds	V_{beds}
Sum of all parts volume	V_B
Material density	ρ
Volume of a single part	Vp
Total number of parts	np
Packing Ratio	$PR = \frac{V_B}{V_{beds}} = \frac{V_P * n_P}{V_{beds}}$
Direct Costs (m_B)	$\mathrm{Cost}(m_B) = \frac{\mathrm{direct\ Cost}}{\mathrm{mass\ unit}} m_B$
Indirect Cost (t_B)	$Cost(t_B) = \frac{\Sigma\ indirect\ cost}{working\ time} t_B$

The application of this method allows the allocation of different cost factors that affect the final cost of a part. Some variables such as Material waste (WB), machine uptime or labour costs may be fine-tuned in order to achieve cost estimated according to individual preferences. Figure 7.14 and 6.17 show two screen captures with both cost calculations (SLS and SLM) for the same STL model shown in Figure 7.13.

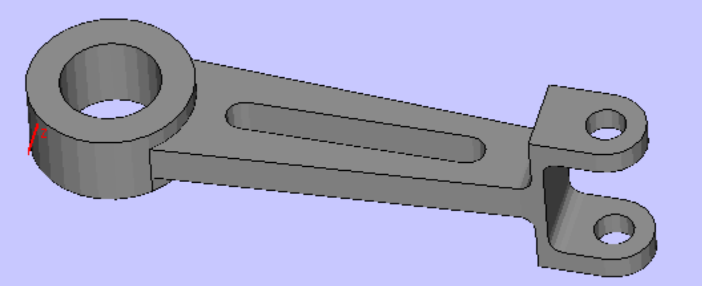
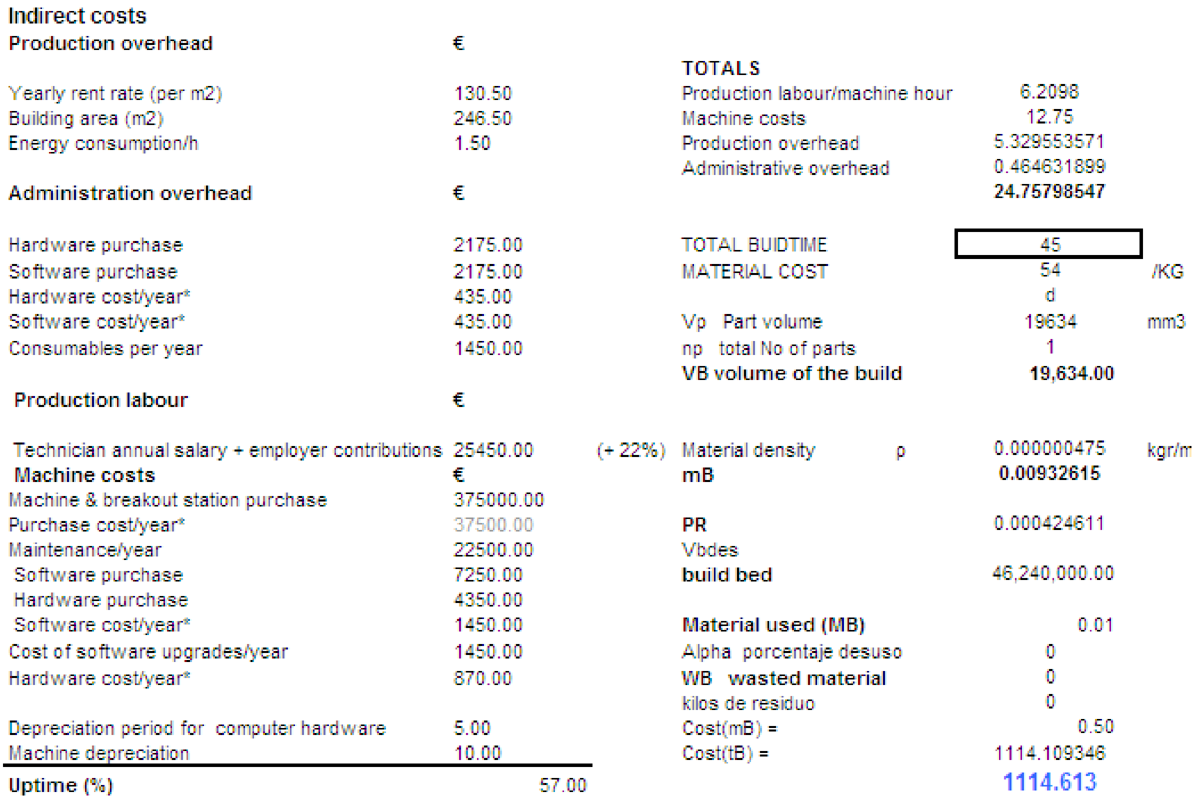


Figure 7. 13 Sample mechanical part simulated



Indirect costs		
Production overhead	€	
Yearly rent rate (per m2)	130.50	
Building area (m2)	246.50	
Energy consumption/h	1.50	
Administration overhead	€	
Hardware purchase	2175.00	
Software purchase	2175.00	
Hardware cost/year*	435.00	
Software cost/year*	435.00	
Consumables per year	1450.00	
Production labour	€	
Technician annual salary + employer contributions	25450.00	(+ 22%)
Machine costs	€	
Machine & breakout station purchase	375000.00	
Purchase cost/year*	37500.00	
Maintenance/year	22500.00	
Software purchase	7250.00	
Hardware purchase	4350.00	
Software cost/year*	1450.00	
Cost of software upgrades/year	1450.00	
Hardware cost/year*	870.00	
Depreciation period for computer hardware	5.00	
Machine depreciation	10.00	
Uptime (%)		57.00

TOTALS			
Production labour/machine hour		6.2098	
Machine costs		12.75	
Production overhead		5.329553571	
Administrative overhead		0.464631899	
		24.75798547	
TOTAL BUIDTIME		45	
MATERIAL COST		54	/KG
		d	
Vp Part volume		19634	mm3
np total No of parts		1	
VB volume of the build		**19,634.00**	
Material density	ρ	0.000000475	kgr/m
mB		**0.00932615**	
PR		0.000424611	
Vbdes			
build bed		46,240,000.00	
Material used (MB)		0.01	
Alpha porcentaje desuso		0	
WB wasted material		0	
kilos de residuo		0	
Cost(mB) =		0.50	
Cost(tB) =		1114.109346	
		1114.613	

Figure 7. 14 Sample datasheet screen with the cost calculation for a sample part for SLS

While “Direct costs” refer mainly to material usage and waste, “Indirect costs” are referred to all the other aspects of manufacturing. As it is shown on Figure 7.15 indirect cost cover almost the whole graph (red). As it is decomposed into its factors it is seen how most of the cost derives from Machine cost. On the other hand for a batch size of 100 parts material costs become the dominant source with a smaller portion of “indirect costs”, as machine costs are amortised by bigger volumes.

Figure 7.17 shows the same costing data applied to the SLM process where the efficiency of the model for allocating different sources of cost can be illustrated.

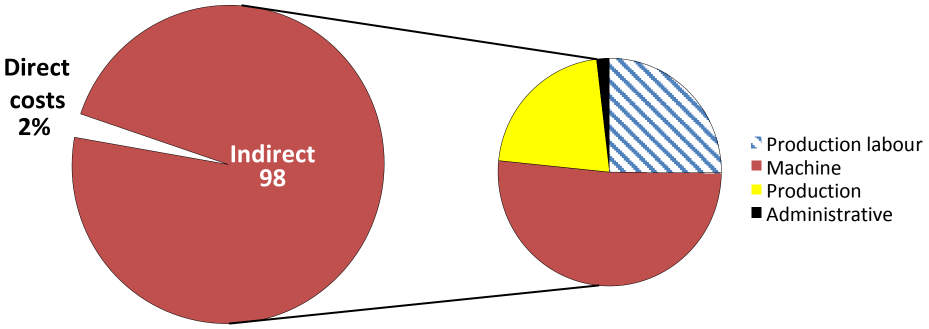


Figure 7. 15 Decomposition of cost factors for SLS (single part)

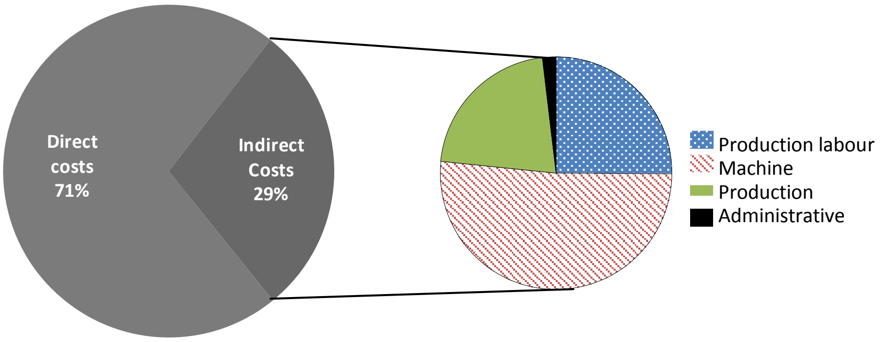


Figure 7. 16 Decomposition of cost factors for SLS (for 100 parts)

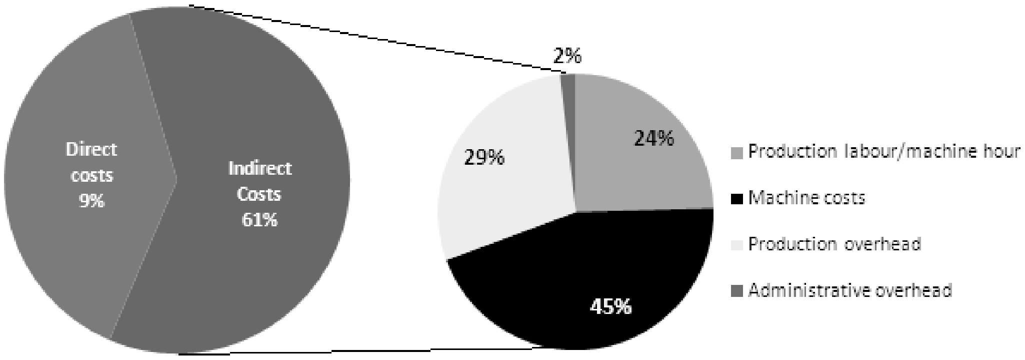


Figure 7. 17 Cost allocation for the SLM process (single part)

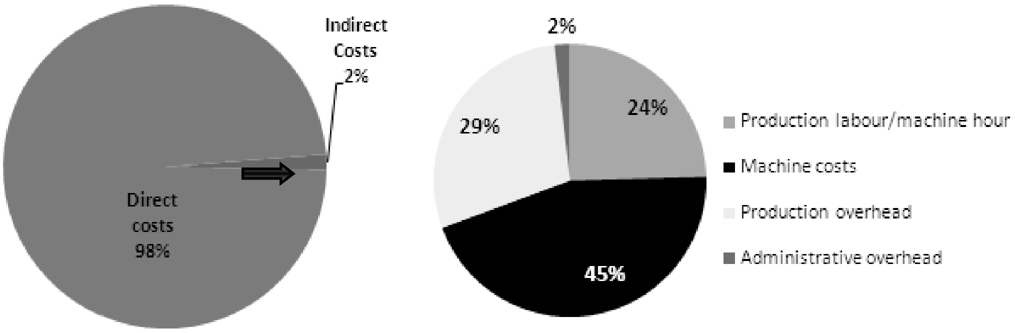
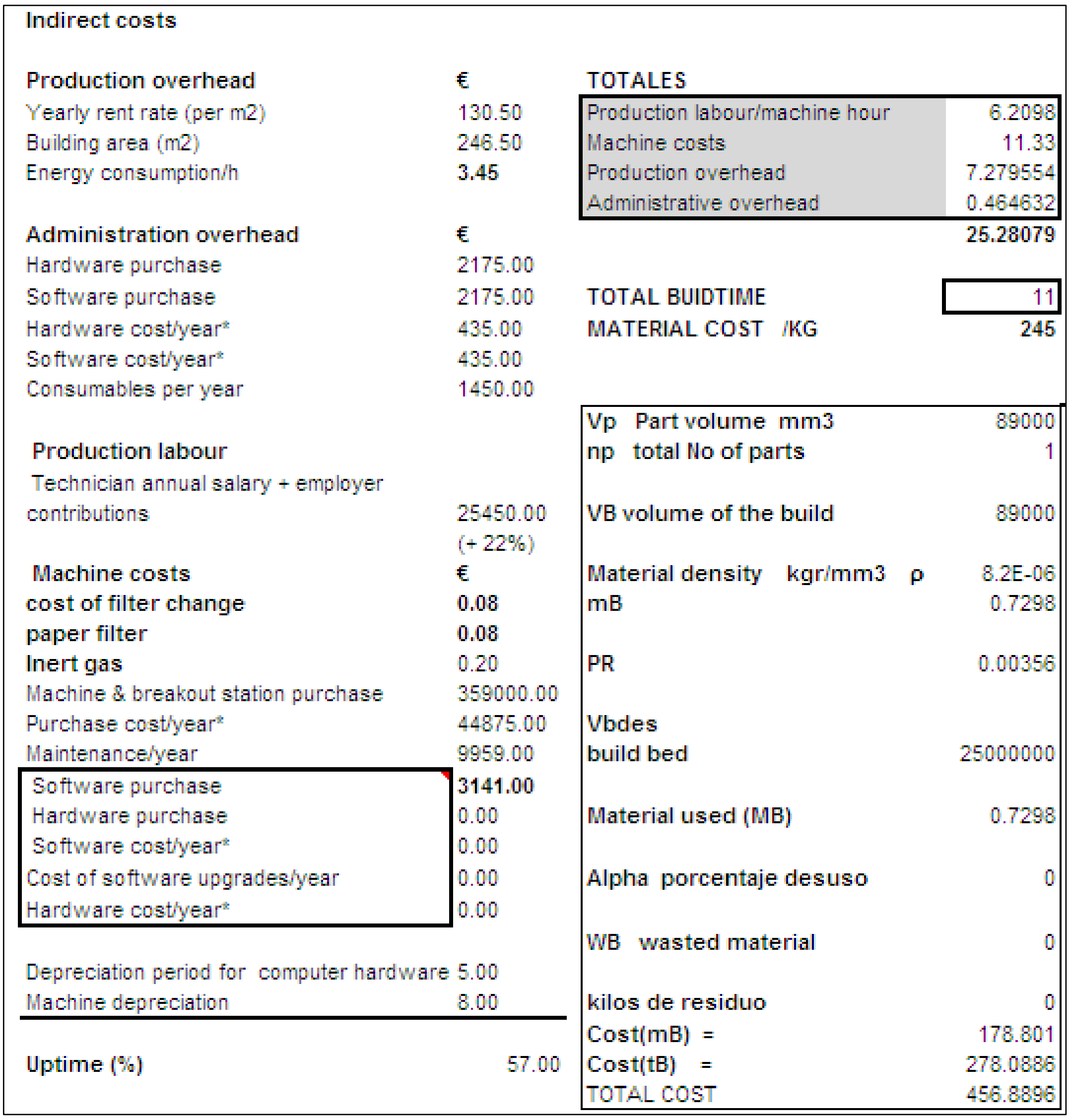


Figure 7. 18 Cost allocation for the SLM process (for 100 parts)



Indirect costs

Production overhead	€
Yearly rent rate (per m2)	130.50
Building area (m2)	246.50
Energy consumption/h	3.45
Administration overhead	€
Hardware purchase	2175.00
Software purchase	2175.00
Hardware cost/year*	435.00
Software cost/year*	435.00
Consumables per year	1450.00
Production labour	
Technician annual salary + employer contributions	25450.00 (+ 22%)
Machine costs	€
cost of filter change	0.08
paper filter	0.08
Inert gas	0.20
Machine & breakout station purchase	359000.00
Purchase cost/year*	44875.00
Maintenance/year	9959.00
Software purchase	3141.00
Hardware purchase	0.00
Software cost/year*	0.00
Cost of software upgrades/year	0.00
Hardware cost/year*	0.00
Depreciation period for computer hardware	5.00
Machine depreciation	8.00
Uptime (%)	57.00

TOTALES	
Production labour/machine hour	6.2098
Machine costs	11.33
Production overhead	7.279554
Administrative overhead	0.464632
	25.28079
TOTAL BUIDTIME	11
MATERIAL COST /KG	245
Vp Part volume mm3	89000
np total No of parts	1
VB volume of the build	89000
Material density kgr/mm3 ρ	8.2E-06
mB	0.7298
PR	0.00356
Vbdes build bed	25000000
Material used (MB)	0.7298
Alpha porcentaje desuso	0
WB wasted material	0
kilos de residuo	0
Cost(mB) =	178.801
Cost(tB) =	278.0886
TOTAL COST	456.8896

Figure 7. 19 Sample datasheet screen with the cost calculation for a sample part for SLM

7.8 Conclusions

Recently there is a growing of interest in applying ANNs to manufacturing, partly due to the expectation that ANN may lead to the realization of truly intelligent manufacturing systems. Their ability to solve problems without the need for a detailed, explicit algorithm for each solution procedure, or rigid mathematical relationships and models, makes them attractive for a wide variety of applications in engineering, and RM might find a potential enabling tool.

However, this approach is not free of some important limitations still to be tackled. Artificial Neural Networks cannot explain their results explicitly, which implies that the user interface of an ANN may not be as friendly or productive as that of an expert system. Furthermore, data used for training and as target results must be efficiently normalized, else it will not work properly or will induce an error depending on the strategy to normalize and retrieve converted data. The configuration of a neural network is usually time-consuming, as one need to use a trial-and-error method to find the proper neural network architecture for a given problem.

The correct parameterization of the model is also key for returning reliable results as an incorrectly or under-parameterized model usually results in biased output. There is a need for a separate validation set when training a given dataset in order to achieve unbiased estimated of ANN performance.

Some of the identified drawbacks when designing ANN-based models is the difficulty to reproduce the same results under different conditions since factors like: initial weights, training data and normalization strategy must be paid attention. Therefore if an ANN-based system is intended to be embedded into an existing software system although the same parameters are used, minor variations in the results may be expected.

The approach used in this research makes use of current knowledge on ANN to obtain reliable build-time estimates for the SLS process from 3 initial parameters previously defined by Ruffo (2006b): Height, Volume, Bounding box, regardless of machine type and operating conditions. The maximum error found during the research is 15% which denotes a clear potential for the ANN-based method to be extrapolated to different RM processes.

Further research will concentrate on ANN modelling for metallic RM processes as well as in the direct cost estimation of Rapid Manufactured parts to be embedded into a more comprehensive RM expert system.

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8. Materials selection for RM

Abstract

This chapter corresponds to the last module of the RMADS system. It deals with the selection of materials according to previously established functional requirements. The selection procedure presented herein is based on a number of previous approaches that go from a general and wide-open screening to a narrowed selection of alternatives.

This module makes use of relational databases built in Ms Access so that RM materials data is easily modified and called from the Matlab application developed. This call is performed through an ODBC procedure which is a standardized routine within the Matlab environment. This application is enriched with the use of selection graphs and coupled with an expert system's capabilities to perform an accurate screening.

8. Materials selection for RM

8.1 Introduction

Materials selection is one of the most important activities during the product design cycle as it dictates the final decision of the processes available to work with the selected options. Chapter 2 introduced “the problem of RM selection” by adopting different means of classification of processes and their corresponding materials options. This section discusses which strategies result more effective for an appropriate selection of materials in Rapid Manufacturing under the focus of machinery design and final functional parts.

This Chapter is not intended to be a comprehensive source for material selection for RM, nor is it intended to be a source for mechanical design material options as there is plenty of information covering this area by recognized authors. This section is rather included as an add-on feature for materials selection for the RMADS system as this is a desirable feature for any comprehensive Computer Aided Design Tool.

The first part presents different criteria guiding the selection of the appropriate material for a given function. Subsequently a series of steps are outlined which guide the user of the RMADS systems to compare key material parameters. The last section presents the material selection user interface implemented in Matlab and a sample case is used to illustrate the interaction of this new module in relation to the process selection and cost estimation slopes.

8.2 On materials selection for design

The selection of the more suitable material/process combination is a key activity requiring a broad knowledge of several aspects of the product design cycle. Riba i Romeva (1997) considers this to be a “*concurrent selection process”* which considers four essential aspects:

- Adequacy to function: The material must fulfil the requirements imposed by the piece or mechanism in terms of physical (density, thermal, optical and electrical properties) and mechanical characteristics (tensile strength, stiffness, frictional properties, etc.)
- Fabrication method: This is also linked to the shape and complexity allowed by candidate or available processes. As for the RMADS system these two issues are addressed in the first module (General selection) where for a given shape and material type the candidate process list is reduced and acceptable processes screened by other user selected attributes
- Cost: While for conventional materials it is easy to obtain material cost-estimates based in the bulk material or cost per kg and considering a fixed waste rate, for RM this is not always possible as there are a number of factors affecting material usage estimation such as the use of support structures, waste and recycling rates.
- Relation with the user: This element includes factors such as possible shapes, colour, textures, post-process and finishing options available such as coatings and other aesthetical factors.

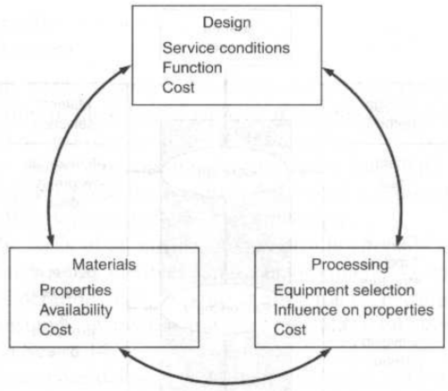


Figure 8. 1 Interrelations between materials, design and processing

Also in the previous list the element of “recycling and disposal” is considered as it is one of the major criteria for selection in the future. However since for RM materials there is not sufficient data on material recycling and disposal policies it has not been included as criterion for the RMADS system.

8.3 The field of Materials for RM

As Grimm (2004) and Wohlers (2006) report on their respective works the beginning of materials for Rapid Manufacturing started out from a reduced choice of alternatives largely dominated by photopolymers with low to moderate functional properties. During the period covering the 90’s and part of the first half of the present decade, materials information available was scarce and difficult to find. On his Doctoral thesis about the development of the “*shape deposition manufacturing process*” Kietzman (1999) makes reference to the material suppliers available at the time. Non-surprisingly the list is dominated by Stereolithography and other resin based technologies which included Ciba, Allied-Signal, Dupont, Zeneca, Coates Brothers, DSM Desotech, Loctite, Asahi Denka, Japan Synthetic Rubber, Teijin Seiki, and other companies, some of them now off the business. However over the last five years the number of material providers and data sources has considerably expanded.

The range of Materials and their suppliers for Rapid Manufacturing has expanded greatly in a few years. As stated by Mueller (2004) “*Nearly every manufacturer now claims to have functional materials that will behave much more like injection moulded plastics.”*However information on these materials is not always readily available. Furthermore, information regarding other material types such as metals, ceramics and composites is hardly available. It has to be carefully compiled manufacturer to manufacturer although it may not always be the best source for reliable material data as it is not contrasted to other sources. Hence the difficulty for analyzing materials for end use manufacture with RM.

One of the tasks undertaken for this chapter is to build a general database for RM materials that can show the basic properties (when available) that matter to make important decisions for product design.
Early materials introduced for RM during the 90’s were brittle, fragile and barely suitable for functional testing, however currently available materials are closely approximating the properties of conventional materials. Selective laser sintering has long used Polyamide and reinforced PA while Metallic laser sintering uses materials more and more similar to Tool Steel and high efficiency alloys such as those based on Titanium, Vanadium and Cobalt-Chrome. The fused deposition process from Stratasys also uses thermoplastic materials including ABS, polycarbonate, and most recently, polyphenylsulfone.
Recently a number of material manufacturers for RM have published datasheets with an unusual claim of material properties that outperform those of their conventional counterparts. For instance processes based

on Metallic Laser Sintering claim better mechanical properties than those exhibited by sand casting or investment casting (Figure 8.2).

Due to the additive nature of these processes the key to achieve similar properties to conventional processes seems to be a higher density (Van Vaerenbergh 2008) the same is true for selective Laser sintering of polyamide. As reported by Wooten (2005) achieving a higher, constant and repeatable density of the final parts was the key to certify sintered nylon material for the fabrication of non-structural parts for the aerospace industry.

	Arcam Ti6Al4V, Typical	Ti6Al4V, Required
Yield Strength (Rp 0,2)	950 MPa	758 MPa
Ultimate Tensile Strength (Rm)	1020 MPa	860 MPa
Elongation	14%	>8%
Reduction of Area	40%	>14%
Fatigue strength* @ 600 MPa	>10,000,000 cycles	
Rockwell Hardness	33 HRC	
Modulus of Elasticity	120 GPa	

*After Hot Isostatic Pressing **ASTM F1108 (cast material) ***ASTM F1472 (wrought material)

Figure 8. 2 Gear Box manufactured with Arcam RBM in Ti6Al4V and the properties claimed by the manufacturer source (http://www.arcam.com)

	Arcam, as-built*	Arcam, after heat treatment*	ASTM F75-07, required
Rockwell Hardness	47 HRC	34 HRC	25–35 HRC
Tensile Strength, Ultimate		960 MPa 140,000 psi	655 MPa 95,000 psi
Tensile Strength, Yield		560 MPa 80,000 psi	450 MPa 65,000 psi
Elongation at Break	Not applicable	20%	>8%
Reduction of Area	Not applicable	20%	>8%
Fatigue limit, Rotating Beam Fatigue		>10 million cycles at 610 MPa (90 ksi)	

*Typical

Figure 8. 3 Acetabular cups with a lattice built in CoCr Alloy by ARCAM AB and material properties. source (http://www.arcam.com)

Relative density		approx. 100 %
Absolute density		7.8 g/cm³
Ultimate tensile strength	as built: horizontal direction	1050 ± 50 MPa
	as built: vertical direction	980 ± 50 MPa
	after stress free annealing	approx. 1200 MPa
Yield strength (Rp 0.2 %)	horizontal direction	540 ± 50 MPa
	vertical direction	500 ± 50 MPa
Elongation at break		25 ± 5 %
Young's modulus	as built	170 ± 20 GPa
	after stress free annealing	approx. 195 GPa
Hardness	as built	230 ± 20 HV1
	ground & polished	250 - 400 HV1

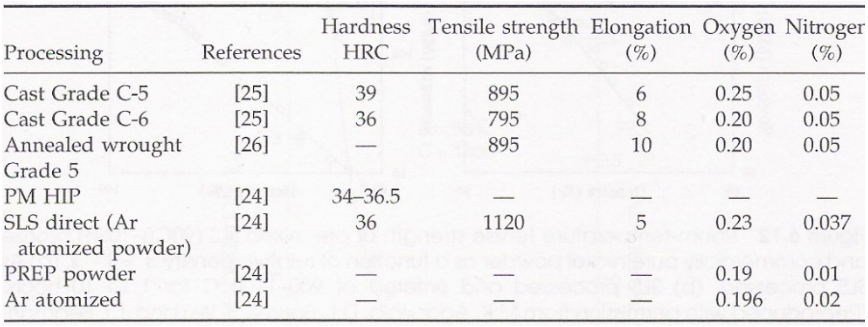
Figure 8. 4 Benchmark part produced on a SLM concept Laser and material specification for Stainless Steel 17-4. Source (Katholieke Universiteit Leuven 2008)

Alloy family	SS + bronze	SS + bronze	SS + bronze
UTS (MPa)	406	682	765
Yield (MPa)	234	420	570
Modulus (GPa)	148	147	151
Elongation (%)	8	2.3	3.8
Remaining porosity	< 1 %	< 1 %	< 1 %
Hardness	60 HRB	30 HRC	35 HRC
Basic Roughness (µm)	R_a = 55	R_a = 55	R_a = 55
Accuracy (mm)	+/- 0.3	+/- 0.3	+/- 0.3
Thermal conductivity (W/mK)	19.2	22.6	18.4
Mean CTE (at 300°C) (10-6/K)	15.4	13.4	12.5
Specific heat (J/kg K)	467	506	497

Figure 8. 5 Sample part produced with a ProMetal R10 machine and Material specifications for the proprietary Stainless Steel(SS) source Sirris (2008)

Table 1 shows the material properties for Ti-6Al-4V corresponding to different manufacturing routes namely: wrought, cast and selective Laser Sintering. It shows how rapid manufactured metals may be compared to conventional processes at least on a few material properties for a sample material.

Table 8 1. roperties of Ti-6Al-4V in cast, wrought, SLS and powder form (Bourell 2006)



Processing	References	Hardness HRC	Tensile strength (MPa)	Elongation (%)	Oxygen (%)	Nitroger (%)
Cast Grade C-5	[25]	39	895	6	0.25	0.05
Cast Grade C-6	[25]	36	795	8	0.20	0.05
Annealed wrought Grade 5	[26]	—	895	10	0.20	0.05
PM HIP	[24]	34–36.5	—	—	—	—
SLS direct (Ar atomized powder)	[24]	36	1120	5	0.23	0.037
PREP powder	[24]	—	—	—	0.19	0.01
Ar atomized	[24]	—	—	—	0.196	0.02

A number of projects have recently appeared, intended to study the properties and behaviour of metal materials and their corresponding build-parameter for a number of metal-based RM technologies. The project TRIALPRO (ASERM 2007) has experimented over the use of RM technologies for functionally demanding applications. It performed a series of mechanical and functional tests in order to determine the behaviour of mechanical parts under stress and normal operating conditions. Some of the conclusions lead to interesting results as shown in Figure 8.6-9 that show some results for the comparison of metal RM technologies (DMLS, Laser Cusing, and SLS). They illustrate the influence of different machine parameters applied to similar materials.

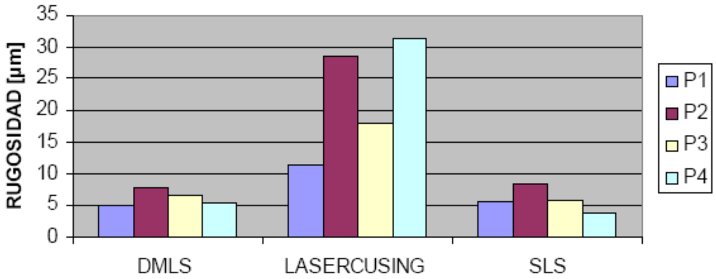


Figure 8. 6 Surface roughness obtained for 3 metal-RM technologies (0˚ inclination) (AIMME 2006)

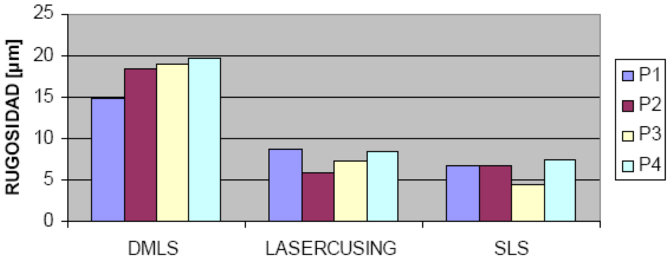


Figure 8. 7 Surface roughness obtained for 3 metal-RM technologies (90˚ inclination) (AIMME 2006)

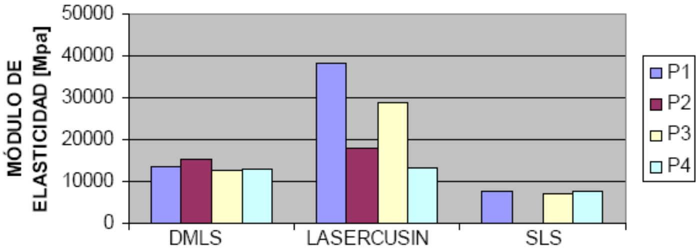


Figure 8. 8 Elastic modulus for test probes (AIMME 2006)

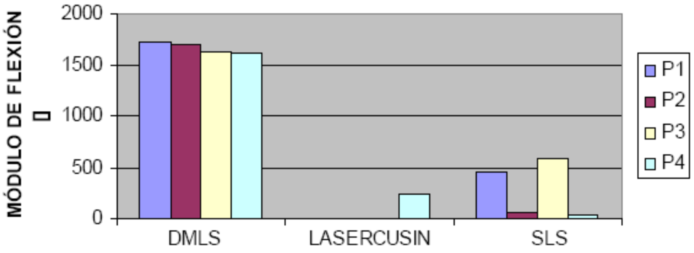


Figure 8. 9 Flexural modulus (AIMME 2006)

A different study on Stainless Steel and Titanium materials was performed by TNO in the Nederland sans AIMME from Spain (AIMME 2006)which included a number of benchmark part tests for a series of metal RM processes including: 3D Printing, Prometal, SLM, and DMLS. The main focus of this project was not the overall performance of the part as in the previous project, but to analyze the dimensional accuracy and stability of the fabrication when dealing with extreme and complex features. Also it explores the difficulties caused by the necessity for building support structures for intricate geometries. Results show a better performance of the SLM machines (Concept and MCP) over the rest of metal forming processes (Figure 8.10).

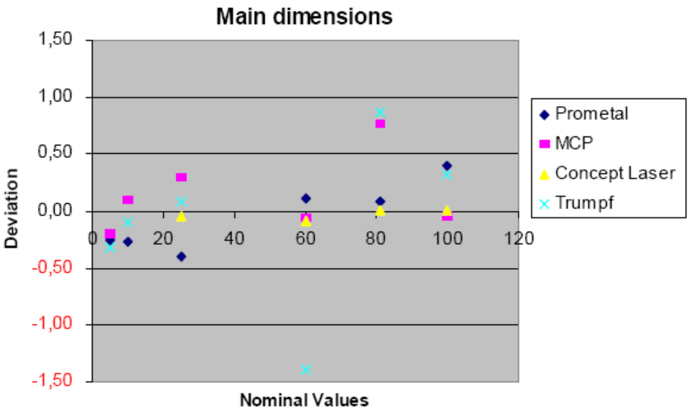
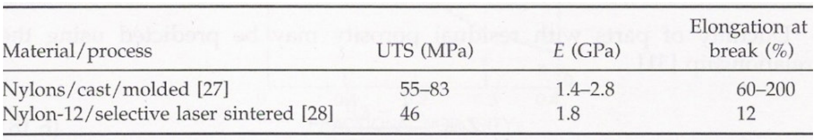


Figure 8. 10 Dimensional accuracy sample chart as shown in the TNO &AIMME report(AIMME 2006)

For processes such as Stereolithography and other resin curing technologies it is not possible to use conventional thermoplastics directly, however recent advancements on these materials include filled resins that mimic a limited range of polymer properties such as stiffness. Although it is not yet common to find industrial applications for photopolymers, they are actually used for functional testing and other end-use applications such as leisure and arts which do not require structural response.

In the case of polymer mechanical properties, layer manufactured parts usually fall short of their injection moulded counterparts. According to Hopkinson, Hague et al. (2005) the reason may be due to porosity and the lack of high pressures used for example in moulding processes. Other factors argued by other research include differences in processing temperature, the powder grain size and shape and the overall density of the final part.

Table 8 2 Differences between laser sintered and conventionally processed nylon



Material/process	UTS (MPa)	*E* (GPa)	Elongation at break (%)
Nylons/cast/molded [27]	55–83	1.4–2.8	60–200
Nylon-12/selective laser sintered [28]	46	1.8	12

Another process with interesting material properties is FDM since this is the only process that works with actual engineering thermoplastics however there few works available that analyse the mechanical properties provided. Ahn, Lee et al. (2004) injection moulded FDM material into STM tensile bars and compared the results vs. extruded cords of the same material with four different angles for the deposition (axial to the bar, 45/-45,0/90, and transverse. Also they varied the air gap parameter (zero and -0.003 inch).

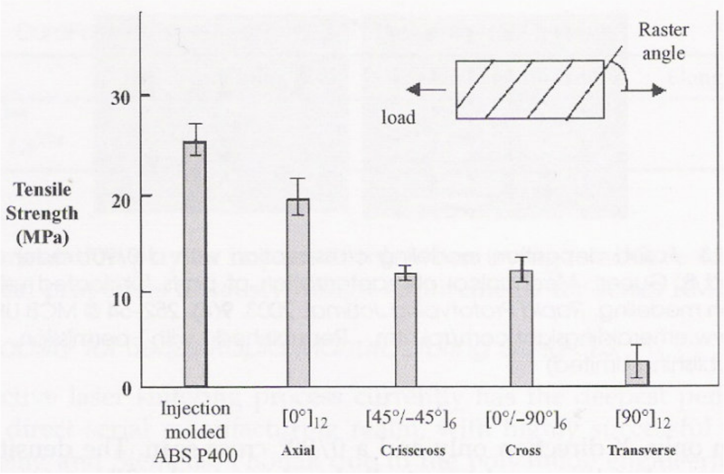


Figure 8. 11 Tensiles Strenght of zero air gap FDM ABS P400 samples. (Ahn, Lee et al. 2004)

The results in Figure 8.11 show an approximation of material properties from 10 to 73% of the injection moulded samples, however as ABS for FDM has proved to exhibit an anisotropic behaviour more testing and experimentation is necessary to obtain other properties such as yield strength, tensile strength, flexural modulus and elongation.

Mueller (2004) discusses the different material properties available for RM processes such as SLA, SLS and FDM. Some of the main conclusion is that although some properties are similar to conventional and engineered thermoplastics, RM materials usually fall short to fulfil other important properties, hence the importance of choosing the right material according to the functional requirements and the primary properties involved in it. To this respect a number of guidelines for the correct selection of RM materials may be listed. This procedure takes into account that not all properties of conventional materials will be achieved and therefore an evaluation of the properties needed is necessary.

1- Identify the end-function of the part. Ej. To support static loads, undergo constant deflections, etc.
2- Determine the key material properties. As stated by Mueller (2004) there can be relatively few material properties that control the performance under the given scenario.
3- Determine how close to the chosen index or property we must approximate. The goal of this step is to draw conclusions from a qualitative screening of available properties data
4- Select the most appropriate RM material for the given case. It means extracting from the database the data of those materials that are close of fulfil the key properties requirements.

Figure 8.12 shows a sample bar graph with the different Flexural Module available from a number of RM materials

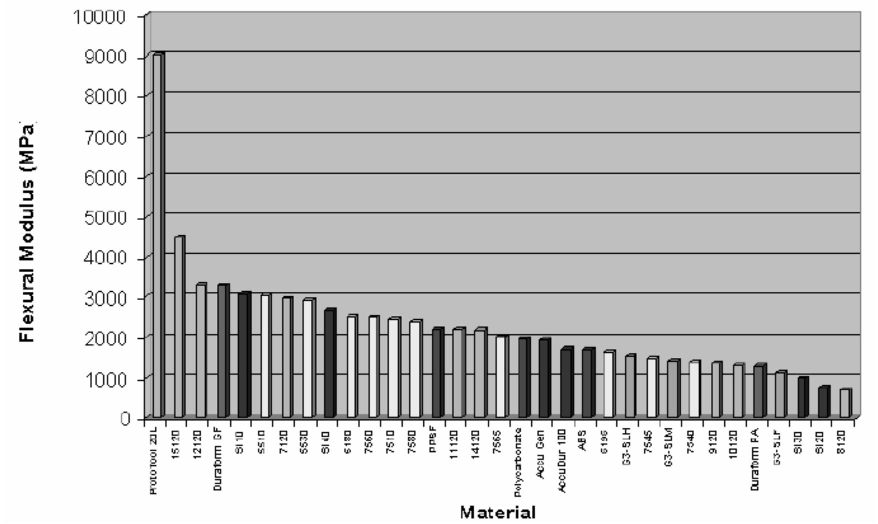


Figure 8. 12 Flexural modulus or RM materials (Mueller 2004)

8.4 The adopted approach for the RMADS system

When selecting a manufacturing process it is important to start with the biggest number of material alternatives as the lack of available information may mean the lost of an opportunity to improve the design. Although some authors that studied in-depth the problem of material selection established that the selection of a definitive material for production constitutes itself a “point of no return” this perception might slightly change for Rapid Manufacturing as due to the low batches usually required and the production of unitary quantities materials may vary from one run to another. The approach adopted for materials selection within the RMADS system follows the method proposed by Ashby (2005) which depicts a series of steps:

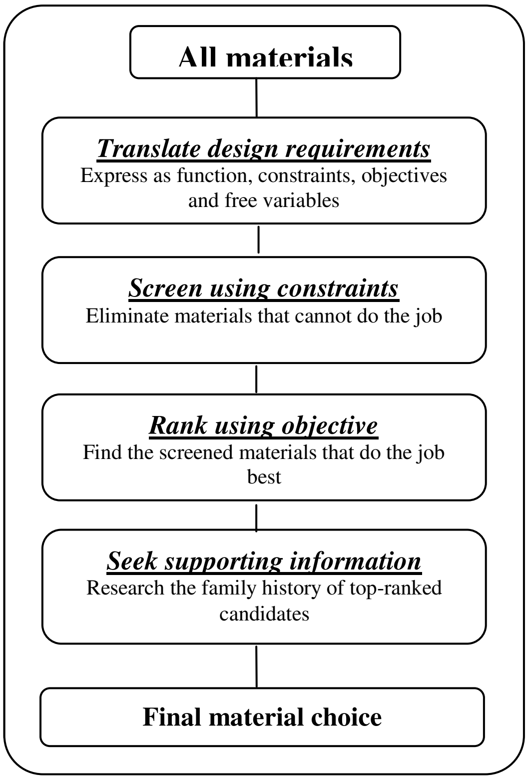
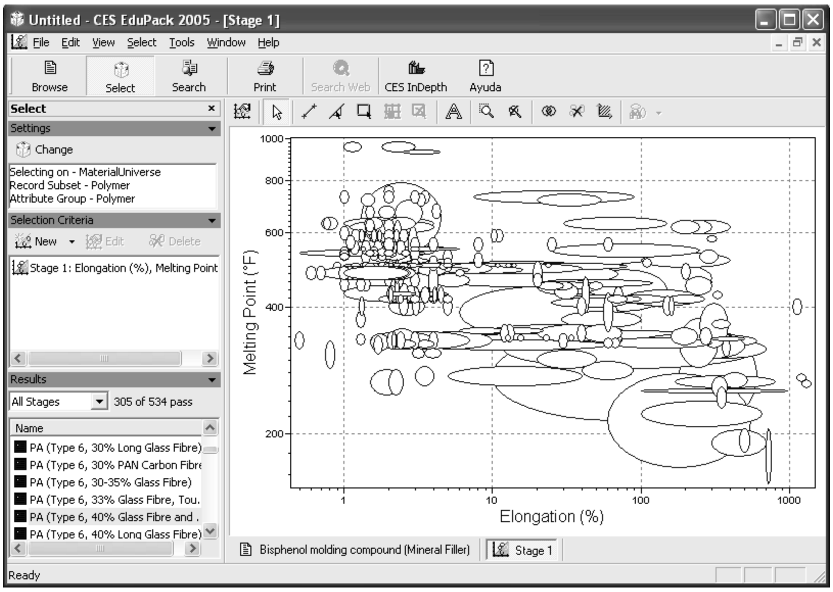


Figure 8. 13 Strategy for materials selection and the four main steps

Ashby and Cebon (1993) introduced the material selection based on performance indices which was best achieved by plotting one material property (or mathematical combination of properties) on each axis of a materials selection chart (Ashby 1993). If process attributes are stored in a database with an appropriate user-interface, selection charts can be created and selection boxes manipulated with much greater freedom.

One reference software for Computer Aided material/process selection that follows the Ashby's approach is CES Edupack (GRANTA 2007) which contains a database of materials organized in a hierarchical manner with the description of the main properties and their typical values. The materials database is connected to online sources for showing additional data besides presenting illustrations and a text description of the process linked to a given material.



Selecting on - MaterialUniverse
Record Subset - Polymer
Attribute Group - Polymer

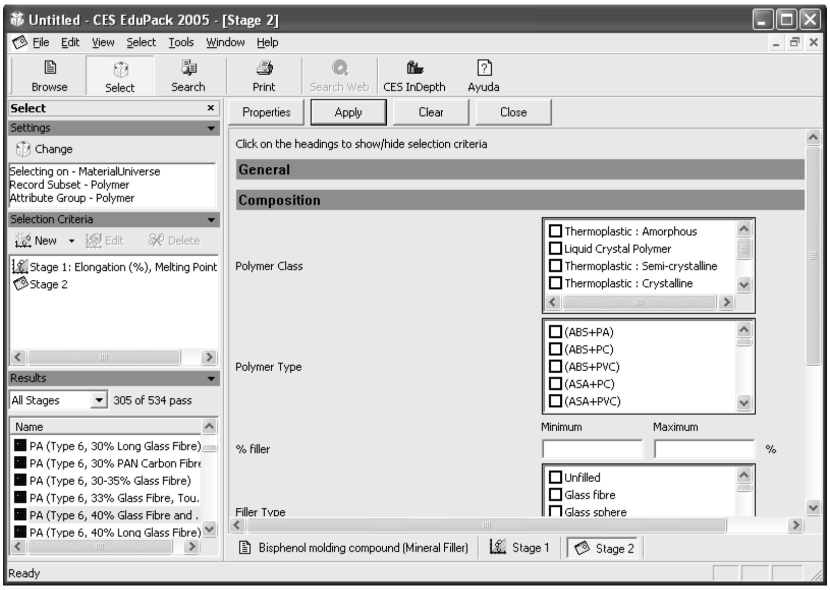
Stage 1: Elongation (%), Melting Point

All Stages 305 of 534 pass

PA (Type 6, 30% Long Glass Fibre)
PA (Type 6, 30% PAN Carbon Fibre
PA (Type 6, 30-35% Glass Fibre)
PA (Type 6, 33% Glass Fibre, Tou.
PA (Type 6, 40% Glass Fibre and .
PA (Type 6, 40% Long Glass Fibre)

Bisphenol molding compound (Mineral Filler) | Stage 1

Figure 8. 14 Initial screening of material properties through graph plotting in the CES software



Selecting on - MaterialUniverse
Record Subset - Polymer
Attribute Group - Polymer

Stage 1: Elongation (%), Melting Point
Stage 2

All Stages 305 of 534 pass

PA (Type 6, 30% Long Glass Fibre)
PA (Type 6, 30% PAN Carbon Fibre
PA (Type 6, 30-35% Glass Fibre)
PA (Type 6, 33% Glass Fibre, Tou.
PA (Type 6, 40% Glass Fibre and .
PA (Type 6, 40% Long Glass Fibre)

Click on the headings to show/hide selection criteria

Polymer Class
☐ Thermoplastic : Amorphous
☐ Liquid Crystal Polymer
☐ Thermoplastic : Semi-crystalline
☐ Thermoplastic : Crystalline

Polymer Type
☐ (ABS+PA)
☐ (ABS+PC)
☐ (ABS+PVC)
☐ (ASA+PC)
☐ (ASA+PVC)

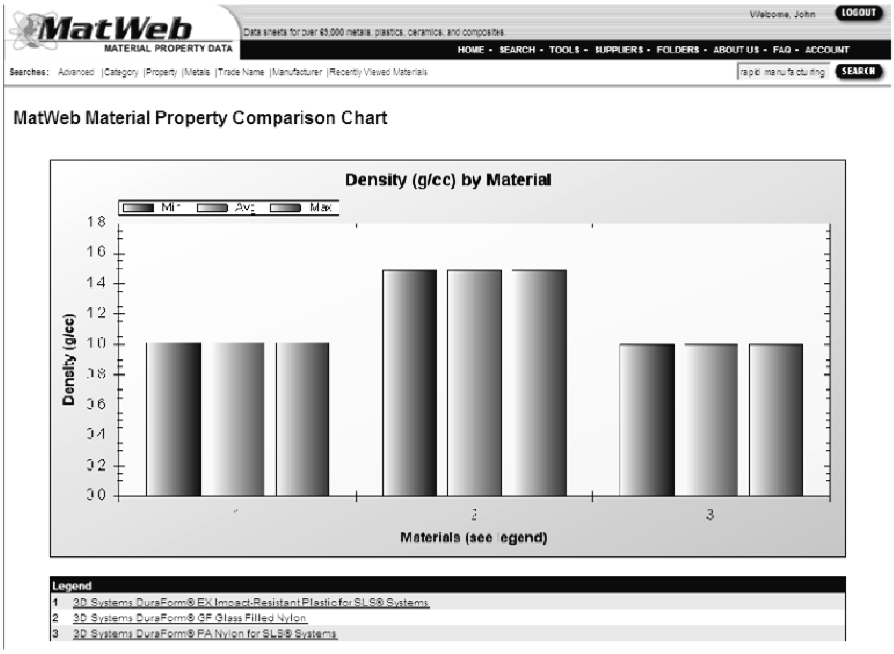
% filler Minimum Maximum %

Filler Type
☐ Unfilled
☐ Glass fibre
☐ Glass sphere

Bisphenol molding compound (Mineral Filler) | Stage 1 | Stage 2

Figure 8. 15 Advanced screening of material properties through limits definition in the CES software

While this software contains information for 98 material classes and 3000 material profiles, the information available for Rapid manufacturing materials is limited and does not cover a wide scope of additive processes. However it is assumed that as any other commercial solution this software is intended to upgrade overtime. Other sources for RM materials selection are online databases. Sources such as (Matweb 2008) offer a wide range of material options. However, as of today only 12 RM materials, mainly for SLA and SLS are included.



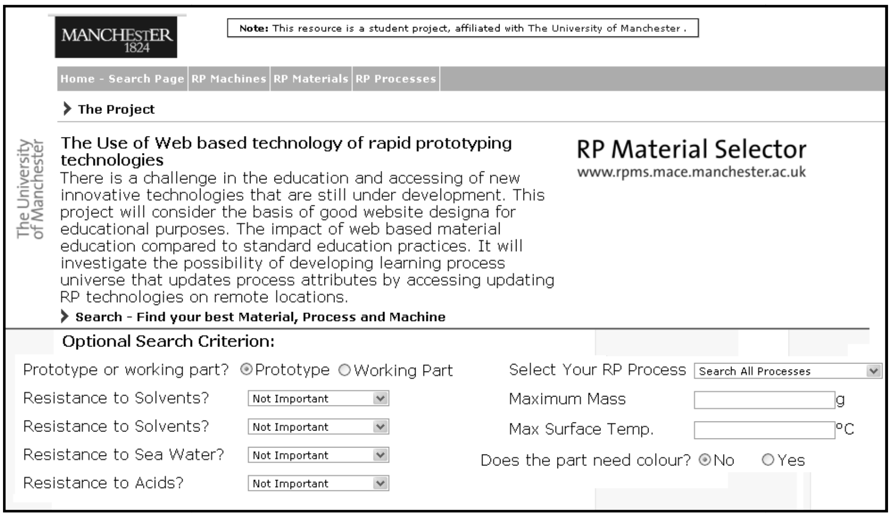
rapid manufacturing

MatWeb Material Property Comparison Chart

1 3D Systems DuraForm® EX Impact-Resistant Plastic for SLS® Systems
2 3D Systems DuraForm® GF Glass Filled Nylon
3 3D Systems DuraForm® PA Nylon for SLS® Systems

Figure 8. 16 Screen capture of the Matweb materials comparison chart for 3 sample cases. (Source www.matweb.com)

Another promising approach to assess the selection of RM materials was presented by Wilde (2007) from The University of Manchester who suggest a number of key parameters to search for the best combination of RM process/material. As of today there are nearly 40 materials stored for a number of RM technologies namely: Sthereolithography, Fused deposition modelling, selective Laser Sintering, Laminated Object Manufacturing, Mutijet Modelling, and Solid ground Curing. Although it is currently online, the system is not operative and does not allow users to try selection parameters.



Note: This resource is a student project, affiliated with The University of Manchester .

The Use of Web based technology of rapid prototyping technologies

There is a challenge in the education and accessing of new innovative technologies that are still under development. This project will consider the basis of good website designa for educational purposes. The impact of web based material education compared to standard education practices. It will investigate the possibility of developing learning process universe that updates process attributes by accessing updating RP technologies on remote locations.

RP Material Selector
www.rpms.mace.manchester.ac.uk

Optional Search Criterion:

Prototype or working part? ● Prototype ○ Working Part
Resistance to Solvents? Not Important
Resistance to Solvents? Not Important
Resistance to Sea Water? Not Important
Resistance to Acids? Not Important
Select Your RP Process Search All Processes
Maximum Mass g
Max Surface Temp. °C
Does the part need colour? ● No ○ Yes

Figure 8. 17 Screen capture of the RP Material selector from The University of Manchester (Source http://www.rpms.mace.manchester.ac.uk/)

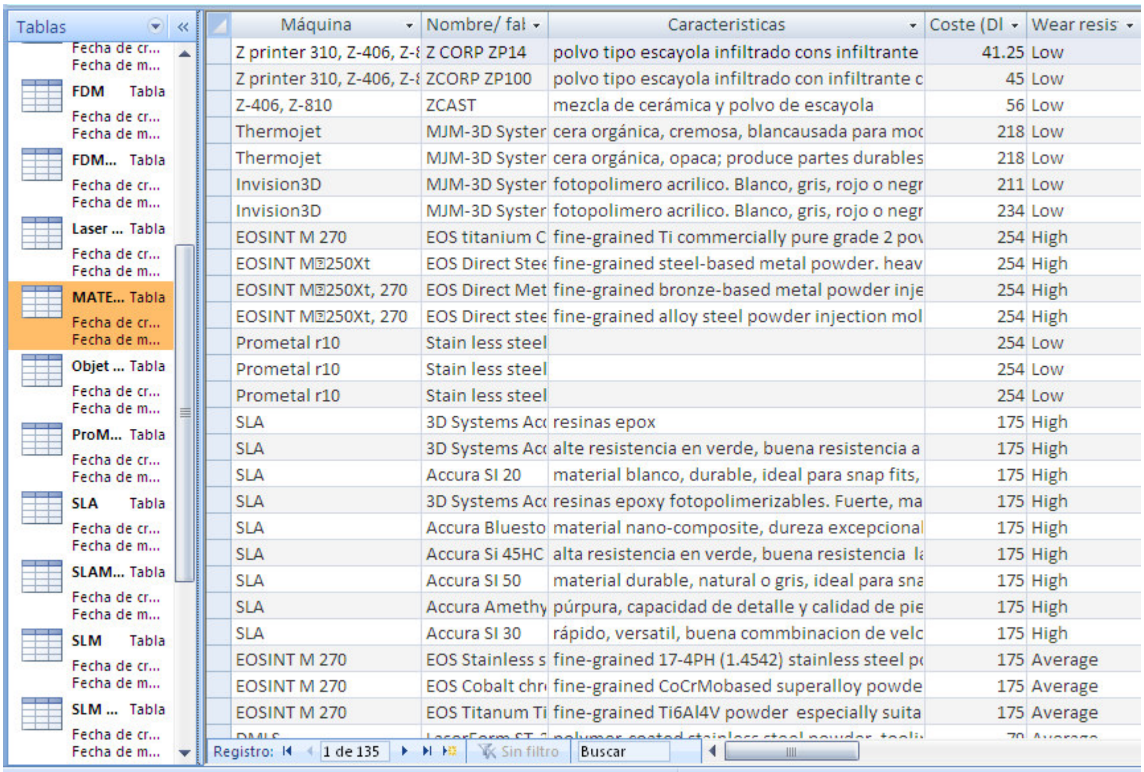
The Rapid Manufacturing Research group at Loughborough University launched the RM consortium which offered on the group's webpage[1] a series of ageing and humidity test especially performed for different combinations of polyamide powder, as the group specializes in selective Laser Sintering, however to date access is restricted and it is not possible to get profound material information.

8.5 Development of the RMADS materials selection module

In order to develop a pilot application for selecting materials within the RMADS system a number a comprehensive compilation of sources was undertaken including manufacturers data (Euromold Materials manufacturers catalogue, 2005- 2007[2]), datasheets provided by specialized service bureaus (Arptech-Ltd 2008) (SolidConcepts 2008) and other specialized independent sources (Ivf Sweeden 2005; Wohlers 2006; CASTLE-ISLAND 2007; eFunda 2007; Matweb 2008). The resulting database has been stored in a MS Excel spreadsheet and is included in Annex8.

The RMADS system makes use of relational databases in order to perform the material selection task. An Ms Access database has been constructed to be used as a Materials repository as it has the following advantages:

- New materials registries can be added, automatically updated and retrieved by a ODBC database call from the RMADS system
- New material properties can be added making it easier to add new constraints to the end user interface
- The data stored in Ms Access can be easily exported to other graphing software such as MS Excel
- Access type databases allow the definition of data types for single columns so that data can be handled as "numerical", "string", "Yes/No", etc.



Máquina	Nombre/ fal	Caracteristicas	Coste (Dl	Wear resis
Z printer 310, Z-406, Z-8	Z CORP ZP14	polvo tipo escayola infiltrado cons infiltrante	41.25	Low
Z printer 310, Z-406, Z-8	ZCORP ZP100	polvo tipo escayola infiltrado con infiltrante c	45	Low
Z-406, Z-810	ZCAST	mezcla de cerámica y polvo de escayola	56	Low
Thermojet	MJM-3D Syster	cera orgánica, cremosa, blancausada para moc	218	Low
Thermojet	MJM-3D Syster	cera orgánica, opaca; produce partes durables	218	Low
Invision3D	MJM-3D Syster	fotopolimero acrilico. Blanco, gris, rojo o negr	211	Low
Invision3D	MJM-3D Syster	fotopolimero acrilico. Blanco, gris, rojo o negr	234	Low
EOSINT M 270	EOS titanium C	fine-grained Ti commercially pure grade 2 pov	254	High
EOSINT M□250Xt	EOS Direct Stee	fine-grained steel-based metal powder. heav	254	High
EOSINT M□250Xt, 270	EOS Direct Met	fine-grained bronze-based metal powder inje	254	High
EOSINT M□250Xt, 270	EOS Direct stee	fine-grained alloy steel powder injection mol	254	High
Prometal r10	Stain less steel		254	Low
Prometal r10	Stain less steel		254	Low
Prometal r10	Stain less steel		254	Low
SLA	3D Systems Acc	resinas epox	175	High
SLA	3D Systems Acc	alte resistencia en verde, buena resistencia a	175	High
SLA	Accura SI 20	material blanco, durable, ideal para snap fits,	175	High
SLA	3D Systems Acc	resinas epoxy fotopolimerizables. Fuerte, ma	175	High
SLA	Accura Bluesto	material nano-composite, dureza excepcional	175	High
SLA	Accura Si 45HC	alta resistencia en verde, buena resistencia la	175	High
SLA	Accura SI 50	material durable, natural o gris, ideal para sna	175	High
SLA	Accura Amethy	púrpura, capacidad de detalle y calidad de pie	175	High
SLA	Accura SI 30	rápido, versatil, buena commbinacion de velc	175	High
EOSINT M 270	EOS Stainless s	fine-grained 17-4PH (1.4542) stainless steel pc	175	Average
EOSINT M 270	EOS Cobalt chr	fine-grained CoCrMobased superalloy powde	175	Average
EOSINT M 270	EOS Titanum Ti	fine-grained Ti6Al4V powder especially suita	175	Average

Figure 8. 18 Screen capture of the materials database

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[1] http://www.lboro.ac.uk/departments/mm/research/rapid-manufacturing/links.html

[2] Online catalog constantly updated on: http://www.euromold.com/english/onlinekatalog/index.php

Table 8.3 Material properties included on the RMADS materials database

Qualitative / material information	Mechanical properties
- Machine / process - Material name - Main features - Cost	- Tensile strength MPa - Tensile modulus MPa - Elongation at break % - Impact strength unnotched Kj/mm - Ball thrust hardness Shore N/mm - Flexural Modulus (MPa) - Density
Functional requirements	**Thermal properties**
- Wear resistance - Corrosion - Absorptivity - Critical - Sanitary - Fire - Electrical - Material type	- Heat deflection Temperature oC - Melting point

However the reader may find a number of gapping areas of material properties definition, as the database is a limited pilot compilation of materials and is based on the information obtained from external sources. Hence it may not match the comprehensiveness of commercial systems, nor is it expected to do so, however it comprises one step in the right direction. Table 8.4 and 7.5 show the difference between the number of parameters offered by commercial software such as the CES Edupack database and the information encountered throughout RM literature and offered by RM service bureaus.

Table 8.4 Material properties covered by the CES Edupack software database

General	***Thermal***
Density lb/in^3	Glass Temperature °F
Price GBP/lb	Heat Deflection Temperature 0.45MPa °F
CO2 creation lb/lb	Heat Deflection Temperature 1.8MPa °F
Production Energy kcal/lb	Maximum Service Temperature °F
Recycle Fraction	Melting Point °F
Oxygen Index %	Minimum Service Temperature °F
Water Absorption	Specific Heat BTU/lb.F
Composition	Thermal Conductivity BTU.ft/h.ft^2.F
% filler	Thermal Expansion =strain/°F
Mechanical	***Processing***
Bulk Modulus 10^6 psi	Linear Mould Shrinkage in/in
Compressive Modulus 10^6 psi	Moulding Pressure Range ksi
Compressive Strength ksi	Processing Temp. (Compression) °F
Elongation %	Processing Temp. (Extrusion) °F
Elastic Limit ksi	***Electrical***
Endurance Limit ksi	Processing Temp. (Injection) °F
Flexural Modulus 10^6 psi	Breakdown Potential V/mil

Fracture Toughness ksi.in^1/2	Dielectric Constant
Hardness - Vickers HV	***Durability***
Hardness - Rockwell M	Dissipation Factor
Hardness - Rockwell R	Resistivity =ohm.cm
Izod Toughness ft.lbf/in^2	Transparency
Loss Coefficient	Flammability
Modulus of Rupture ksi	Fresh water
Poisson's Ratio	Organic Solvents
Shape Factor	Oxidation at 500c
Shear Modulus 10^6 psi	Sea water
Tensile Strength ksi	Strong/weak Acid
Young's Modulus	Strong/weak Alkalis
	UV
	Wear

Table 8.5 Most common material properties published in literature (Wohlers 2006) (Left.) RM material properties offered by service bureaus (Right)

Mechanical properties		***Mechanical properties***
Tensile Strength	⇨	Tensile Strength
Tensile Modulus		Tensile Modulus
Flexural Modulus		Impact strength
Elongation at break		hardness
Elongation at yield		
Impact strength		
hardness		
Thermal		
Glass transition temperature		
Heat deflection		
Cost		

The difficulties exposed before, about data retrieval for RM materials is exposed on Figure 8.19 where it is shown how Mechanical properties are known for a greater number of materials while Thermal properties are less studied. Aesthetical and functional properties are seldom included by manufacturers being frequently available through research performed by third parties.

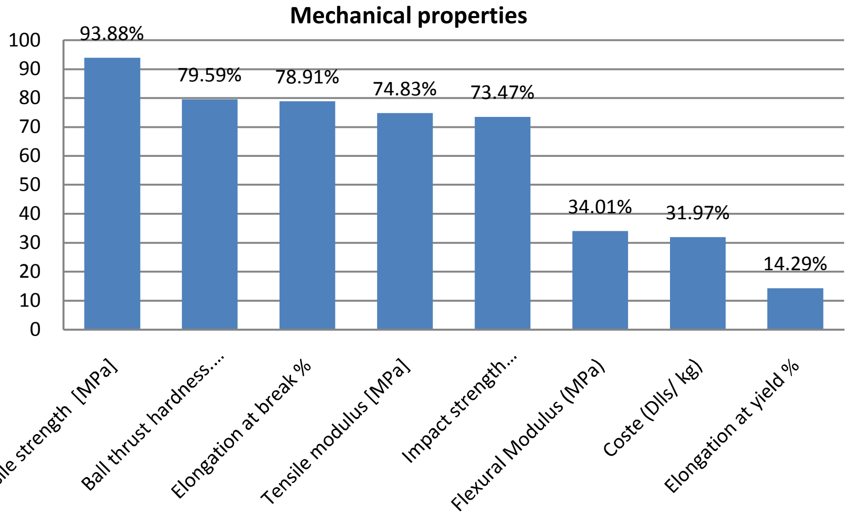


Figure 8. 19 Percentage of available information for RM materials in the database (Mechanical properties)

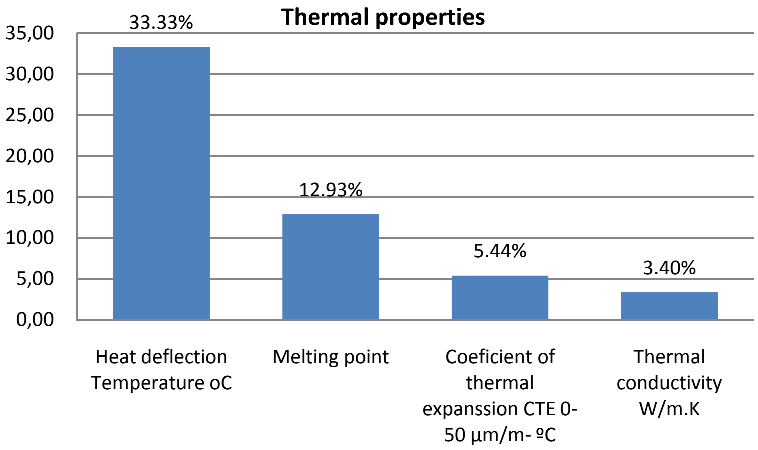


Figure 8. 20 Percentage of available information for the RM materials database (thermal properties)

Also, the number of materials available gives an idea of the importance of a given RM technology. The RMADS materials database contains the materials distribution shown in Table 8.6. Since the SLA process is one of the most widespread technologies it is not surprise that the number of material formulations greatly exceeds the number of options available for newer technologies, specially the metal based ones.

Table 8.6 Number of materials included in the database. Distributed by process

Process name	Acronym	Number of materials
Stereolithography	SLA	80
Selective Laser Sintering	SLS	28
Metal Laser Sintering	DMLS	9
Fused Deposition Method	FDM	12
3D printing	3DP	7
Objet polymer printing	-	7
Selective Laser Melting	SLM	5
Prometal	-	3
Electro Beam Melting	EBM	2
Laminated Object Manufacturing	LOM	3

8.5.1 Rules for selecting materials

Material selection is based on assigning restrictions according to the final part use. The model presented herein makes use of such restrictions to limit the number of surviving materials that fulfil the user requirements. Restrictions are implemented so that new additional criteria can be easily added to the program code.

Consider the attribute “Wear resistance” which has three different possible alternatives:

- High
- Average
- Low

Selecting the alternative “Low” makes the 156 materials potential candidates. However if a second attribute is added such as “corrosion resistance” and the alternative “High” is selected, the number of candidate materials will be accordingly resized. The same is true for the additional attributes that may be added to the system, this comprises the main selection engine

as shown below.

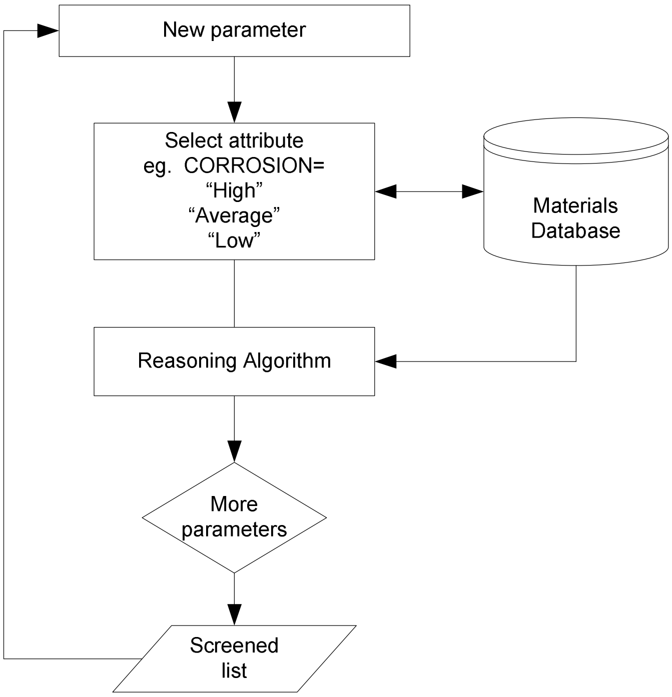
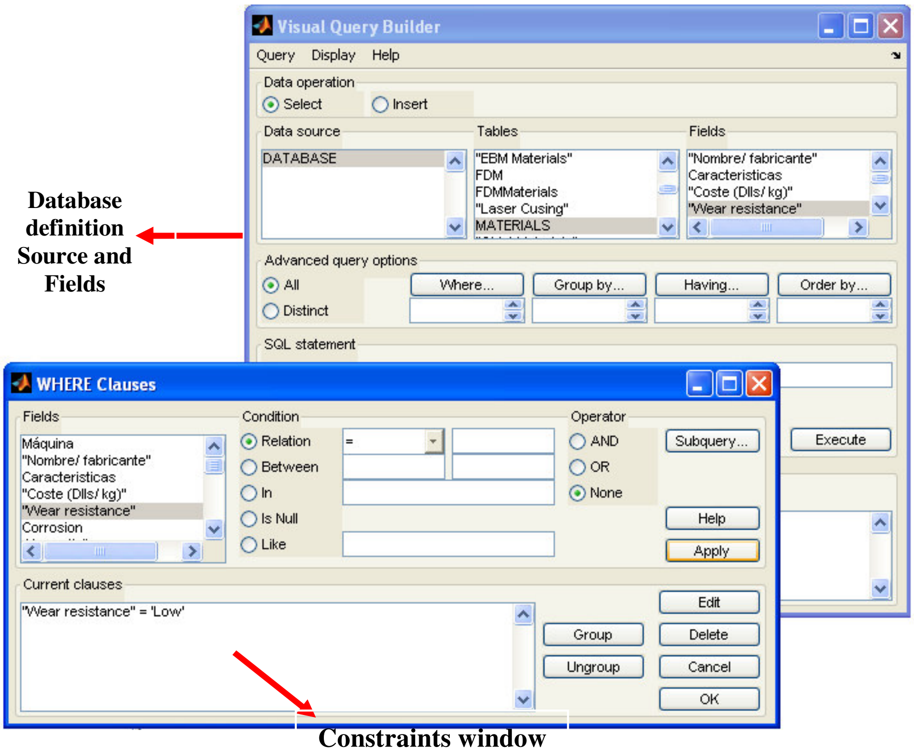


Figure 8. 21 Diagram of the RMADS materials selection scheme

Operation number 1 on the previous graph is achieved by making the appropriate database call to select only the desired attribute. It is possible to make a call to any Ms Access database from within the Matlab code by using the “*Visual Query Builder”* that is, an automated method to query data sources.



Data operation: ● Select ○ Insert

Data source: DATABASE

Tables: "EBM Materials"
FDM
FDMMaterials
"Laser Cusing"
MATERIALS

Fields: "Nombre/ fabricante"
Caracteristicas
"Coste (Dlls/ kg)"<br>"Wear resistance"

Advanced query options: ● All ○ Distinct

WHERE Clauses — Fields: Máquina
"Nombre/ fabricante"
Caracteristicas
"Coste (Dlls/ kg)"<br>"Wear resistance"
Corrosion

Condition: ● Relation =

Operator: ● None

Current clauses: "Wear resistance" = 'Low'

Database definition Source and Fields

Constraints window

Figure 8. 22 The visual Query builder interface in Matlab

The following is a sample code that corresponds to the previous window. It is possible to se that the restriction of the material property is imposed on line 5, while the preferred attribute is selected on line 6.

```
setdbprefs({'DataReturnFormat','ErrorHandling','NullNumberRead','NullNumberWrite','NullStringRead','NullStringWrite','JDBCDataSourceFile'},{'cellarray','store','NaN','NaN','null','null',''});
conn = database('DATABASE','','');
wear_high = exec(conn,'SELECT ALL "Nombre/ fabricante","Wear resistance" FROM MATERIALS WHERE "Wear resistance" = ''High''  ');
```

Once the selected attributes are extracted from the database the Reasoning algorithm that generates the final materials list is based on a vector matching strategy, i.e. the material vectors that result from the user preferences will be compared so that only those materials that appear in every vector will be included in the final list as potential material candidates. This is achieved by performing a number of basic "Set theory" operations.

Consider sets A, B and C as collections of objects which contain a number of material alternatives as follows:

$$A = \{MaterialA, MaterialB, MaterialC\}$$

$$B = \{MaterialX, MaterialB, MaterialY\}$$

$$C = \{MaterialZ, MaterialW, MaterialB\}$$

Our interest is to extract only those materials that fulfil the three restrictions, i.e. the elements that are present in every set. This is described by an intersection operation:

$$A \cap B \cap C = \{MaterialB\}$$

That is: $\{\mathrm{MaterialB} \in \mathrm{A}: \mathrm{MaterialB} \in \mathrm{B}: \mathrm{MaterialB} \in \mathrm{C}\}$

The following case study shows the use and implementation of the RMADS materials selection module through a user interface developed in Matlab.

8.6 Case Study: Connecting Road

The case study presented in this section is extracted from the TRIALPRO project "Prediction of the behaviour of Rapid Manufactured parts under real service conditions" (ASERM 2007). They illustrate the initial product specifications for two mechanical parts with specific functional needs. Since the intention of the TRIAPRO project is to verify the suitability of Rapid Manufacturing technologies for end use parts, the results generated by the RMADS materials selection module will be contrasted against previous results. A plastic connecting road (Figure 8.23) originally designed as a PA injection moulded part is to be analysed in order to check viability for RM fabrication. Although it is a special design the main function is still the conventional motion conversion and transmission.

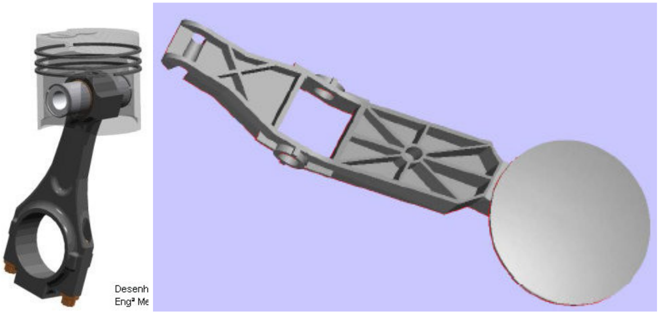


Figure 8. 23 Special design of a connecting road developed by the AITIIP centre (Zaragoza, Spain) and analyzed within the TRALPRO project

Step 1. Identifying the end use and main functional requirements (as provided by the designer)

- Material required is plastic
- Admissible temperature ranges:
  - minimum temperature 0,0 °c
  - Maximum temperature 60 °c
- Service life = 4 years
- Vertical pressure ranges= 16 – 25 kg
- Daily cycles requires = 200

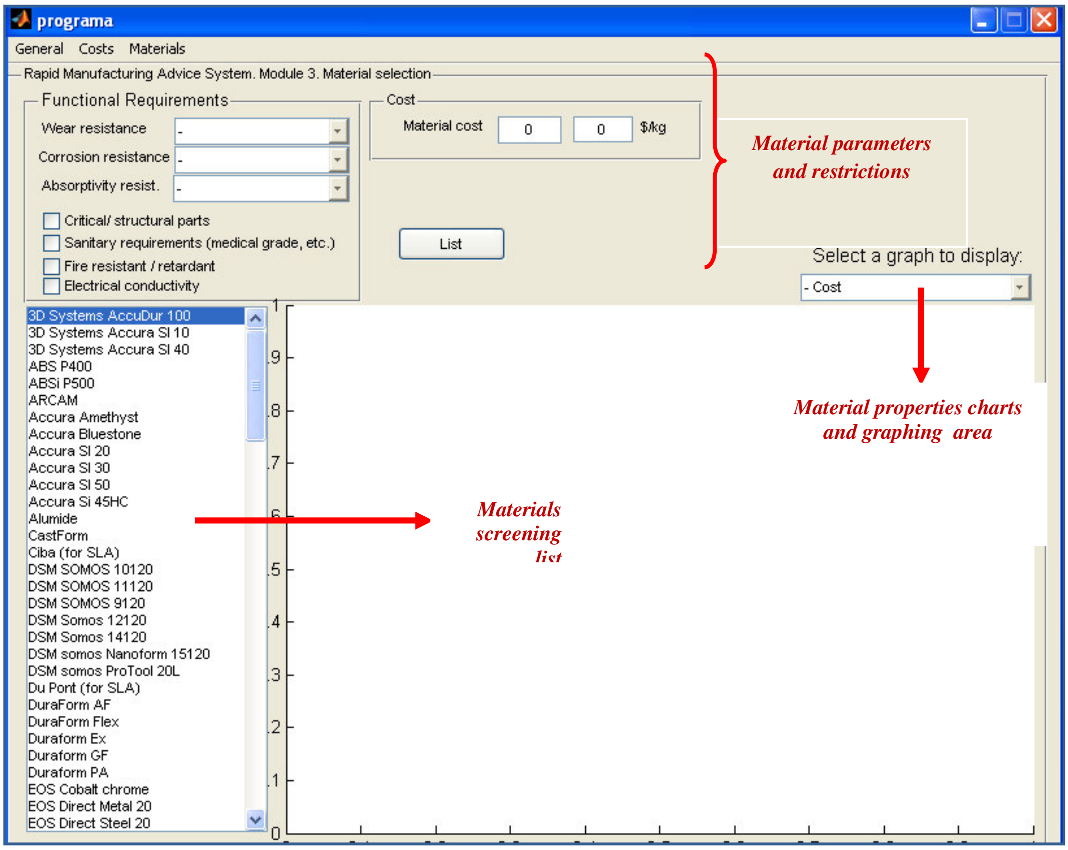
Step 2. Determine key material properties.

The key properties to be analyzed comprise a) mechanical and b) thermal.

a) Mechanical properties

As the part will be subjected to repetitive cycles with moderate loads one important parameter for the analysis is "Wear resistance". We assume that the production material will have a factor of safety designed in so that it will not fail if a temporary over-load or wear conditions change. Therefore the part will be considered as a structural element.

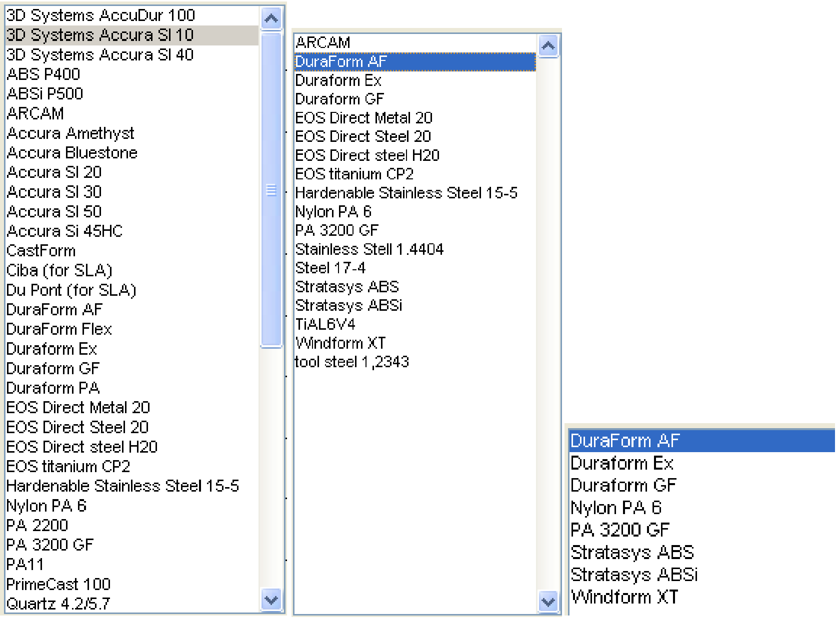
Figure 8.25 shows the different screening phases that occur during selection. On a first stage the original number of materials is maintained. After Wear resistance is set to "High" the number of surviving materials is reduced to 54. Then when the "Critical part" criterion is applied, options drop to 18 alternatives. From these materials only 8 are polymers, hence when the restriction of "Material type" is set to "Polymer" the range of options is reduced to 8.



Wear resistance: -
Corrosion resistance: -
Absorptivity resist.: -
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity
Material cost 0 0 $/kg
Select a graph to display: - Cost

3D Systems AccuDur 100
3D Systems Accura SI 10
3D Systems Accura SI 40
ABS P400
ABSi P500
ARCAM
Accura Amethyst
Accura Bluestone
Accura SI 20
Accura SI 30
Accura SI 50
Accura Si 45HC
Alumide
CastForm
Ciba (for SLA)
DSM SOMOS 10120
DSM SOMOS 11120
DSM SOMOS 9120
DSM Somos 12120
DSM Somos 14120
DSM somos Nanoform 15120
DSM somos ProTool 20L
Du Pont (for SLA)
DuraForm AF
DuraForm Flex
Duraform Ex
Duraform GF
Duraform PA
EOS Cobalt chrome
EOS Direct Metal 20
EOS Direct Steel 20

Figure 8. 24 Initial screen of the RMADS materials selection module



3D Systems AccuDur 100
3D Systems Accura SI 10
3D Systems Accura SI 40
ABS P400
ABSi P500
ARCAM
Accura Amethyst
Accura Bluestone
Accura SI 20
Accura SI 30
Accura SI 50
Accura Si 45HC
CastForm
Ciba (for SLA)
Du Pont (for SLA)
DuraForm AF
DuraForm Flex
Duraform Ex
Duraform GF
Duraform PA
EOS Direct Metal 20
EOS Direct Steel 20
EOS Direct steel H20
EOS titanium CP2
Hardenable Stainless Steel 15-5
Nylon PA 6
PA 2200
PA 3200 GF
PA11
PrimeCast 100
Quartz 4.2/5.7

ARCAM
DuraForm AF
Duraform Ex
Duraform GF
EOS Direct Metal 20
EOS Direct Steel 20
EOS Direct steel H20
EOS titanium CP2
Hardenable Stainless Steel 15-5
Nylon PA 6
PA 3200 GF
Stainless Stell 1.4404
Steel 17-4
Stratasys ABS
Stratasys ABSi
TiAL6V4
Windform XT
tool steel 1,2343

DuraForm AF
Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF
Stratasys ABS
Stratasys ABSi
Windform XT

Figure 8. 25 Material screening phases generated by applying restrictions a) Initial list. b) Wear resistance high c) Critical parts & Material type = Polymer

b) Thermal Properties

The range of temperatures specified in the initial product requirements makes it necessary to define a measure or indicator for Thermal properties. Heat deflection temperature (HDT) will be used to approximate the temperature resistance of the RM materials to the specified requirements.

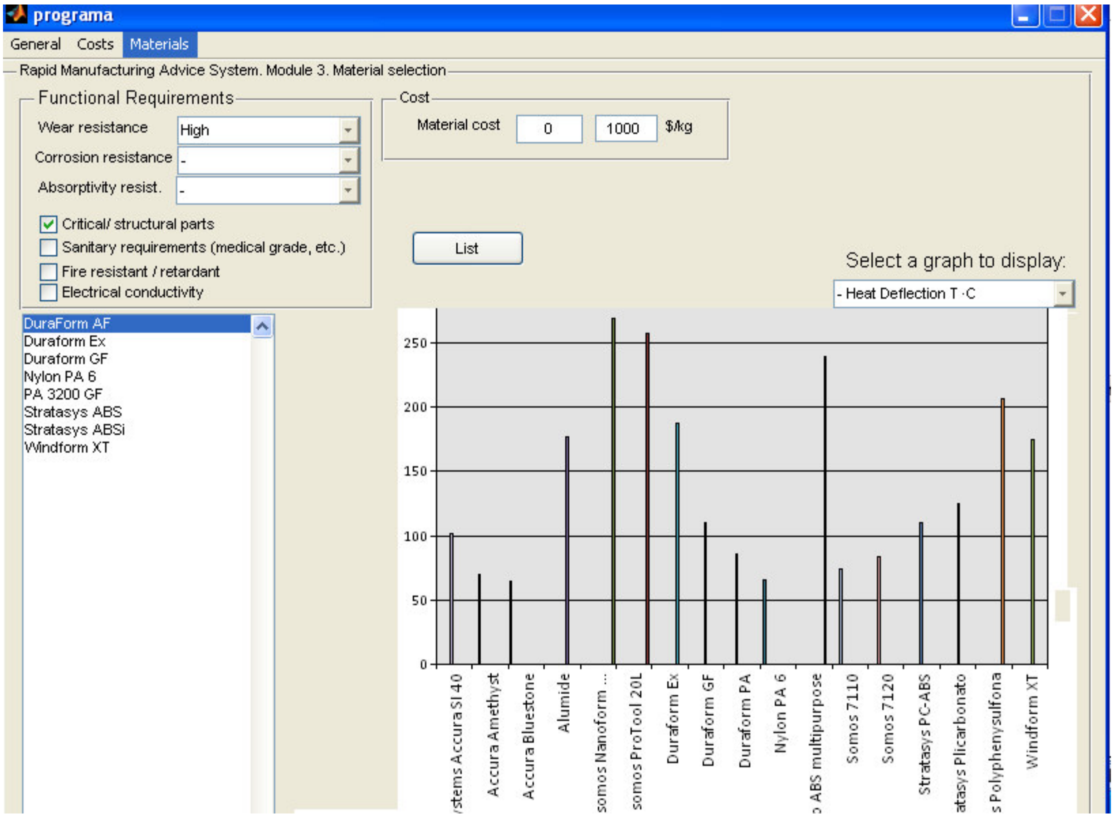
In order to show the HDT data the List box at the right-hand of the screen is activated and the "Heat Deflection Temperature" graph displayed as shown in Figure 8.27. From the HDT graph it is observed that most of the materials that survived the previous screening phase also fulfil the thermal requirements. Additionally if cost is a defining factor for selecting materials it is possible to add a new restriction to the final list as shown in Figure 8.26 when the cost limit is set to 100$ alternatives are reduced to four choices.

Cost
Material cost 0 100 $/kg

Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF

Figure 8. 26 The result of adding a costing restriction on the final result

The result shows that three materials for Selective Laser Sintering and one material for Fused Deposition Method would be capable of providing the required specifications for the analyzed part. While the current user interface is limited to a few functional requirements, more parameters can be easily added so that the user can count with more valuable information.



Rapid Manufacturing Advice System. Module 3. Material selection

Functional Requirements

Wear resistance: High

Corrosion resistance: -

Absorptivity resist.: -

☑ Critical/ structural parts

☐ Sanitary requirements (medical grade, etc.)

☐ Fire resistant / retardant

☐ Electrical conductivity

Cost

Material cost: 0 – 1000 $/kg

Select a graph to display: - Heat Deflection T ·C

DuraForm AF
Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF
Stratasys ABS
Stratasys ABSi
Windform XT

Figure 8. 27 Figure The RAMDS screen capture with the HDT on the graph area

8.7 Difficulties encountered during the database building

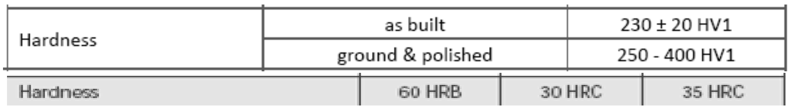
One recognized weakness of the whole RM industry is the lack of standardization in its different components. Jurrens (1999) lists some areas being addressed (Table 8.7) however few advances have been reached. Besides the incipient accordance over the need of standardization another factor is the lack of sufficient literature as the area of RM is a relatively new area from the perspective of materials and testing specifications. A few previous works have highlighted this aspect. Munguía (2007) showed the necessity of material testing standards by citing a case where a service provider running a DMLS equipment needed to certify the hardness of a machinery part but no standards were available to certify this, partly due to the layered nature of Laser Sintered Parts.

Table 8.7 Current standards for different RM areas (Jurrens 1999)

Software / exchange formats	The STL data format for the interface between CAD and RP is an industry de facto standard
Testing Standards	ASTM subcommittee E28.16 on rapid prototyping has addressed mechanical testing standards, specifically for evaluation of the tensile strength of RP parts
Repetability / quality evaluation	Several RP ``benchmark'' parts have been developed for particular user communities to evaluate RP processes. These benchmark parts are typically available for industry-wide use
Material properties	Various specifications for RP materials have been developed to describe material properties and characteristics. Many times these specifications have used a similar format to represent the material data.

During the compilation of RM material properties a number of issues raised that show the necessity of standardization at least for materials testing. A number of situations are described

1) Units provided by material suppliers and services bureaus are not unified, undefined and sometimes percentages are used instead of actual values e.g.



a)

Hardness	as built	230 ± 20 HV1
	ground & polished	250 - 400 HV1

b)

Hardness	60 HRB	30 HRC	35 HRC

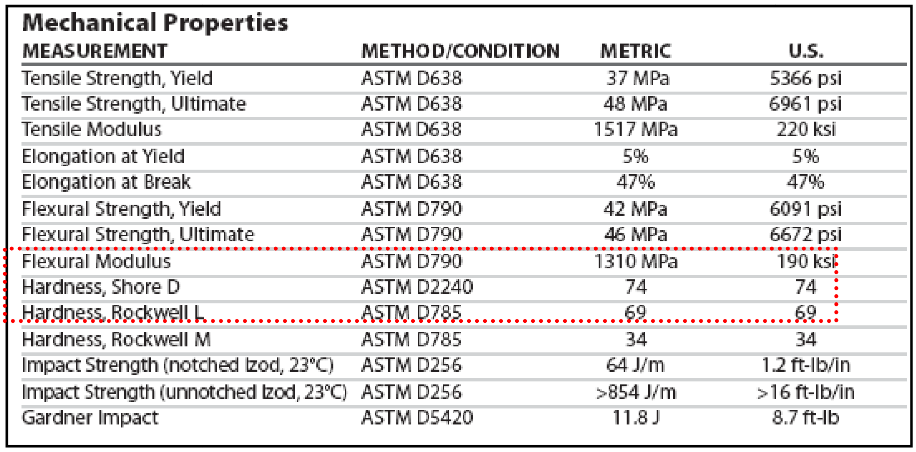
Figure 8. 28 Hardness units provided by two different service providers for Stainless Steel Material

2) Some measurements like the Thermal units are not reported under the same testing conditions:

Table 8.8 Variability of the specified units for the Coefficient of thermal expansion

Specification 1	Specification 2
Coefficient of thermal expansion CTE 20-100 µm/m- ºC	Coefficient of thermal expansion CTE 0-50 µm/m- ºC

3) Hardness testing procedures vary for different material datasheets. Only few materials have complete information available on performed hardness tests and the testing method.



Mechanical Properties

MEASUREMENT	METHOD/CONDITION	METRIC	U.S.
Tensile Strength, Yield	ASTM D638	37 MPa	5366 psi
Tensile Strength, Ultimate	ASTM D638	48 MPa	6961 psi
Tensile Modulus	ASTM D638	1517 MPa	220 ksi
Elongation at Yield	ASTM D638	5%	5%
Elongation at Break	ASTM D638	47%	47%
Flexural Strength, Yield	ASTM D790	42 MPa	6091 psi
Flexural Strength, Ultimate	ASTM D790	46 MPa	6672 psi
Flexural Modulus	ASTM D790	1310 MPa	190 ksi
Hardness, Shore D	ASTM D2240	74	74
Hardness, Rockwell L	ASTM D785	69	69
Hardness, Rockwell M	ASTM D785	34	34
Impact Strength (notched Izod, 23°C)	ASTM D256	64 J/m	1.2 ft-lb/in
Impact Strength (unnotched Izod, 23°C)	ASTM D256	>854 J/m	>16 ft-lb/in
Gardner Impact	ASTM D5420	11.8 J	8.7 ft-lb

Figure 8. 29 Technical data available for the DuraForm Ex material

4) Material data reported by American and European manufacturers usually makes reference to different standards which on most cases are not comparable

One final difficulty arises when instead of a central value the range of properties is presented in intervals, meaning that final properties depend on other parameters such as: machine laser power, part orientation, isotropy/ anisotropy, et al. including an element of uncertainty in the data reliability.

8.8 Conclusions

This section presented a Method for the retrieval, analysis and selection of Rapid manufacturing materials based on relational databases and the graphical representation of material properties. The graphical screening method had been introduced by professor Ashby; later work on the same field follows similar patterns including the most recent Selection software therefore this system has been modelled on the same line.

As a result the RMADS materials module is able to generate:

- Feasible materials that fulfil a series of functional requirements
- Search and extract from a database those materials within a defined property range
- Illustrate with on-demand graphs additional properties for a detailed materials comparison

Although the RMADS system displays currently available RM materials it relays on the information published by third parties and does not include self reproduced material testing as it would form part of further research. Therefore it is important to notice the following points when using this system:

- Most of the available RM materials are still intended for prototyping. Therefore final properties may not even approach those of real materials, especially when speaking of thermoplastics.
- Components with multiple requirements (e.g. thermal, mechanical, functional, cost) will be difficult to analyze due to the lack of information on key parameters, therefore the final material recommendation generated by this system may not be the ideal for production, and prototyping phases could be needed.
- It is unlikely to predict failure modes and ageing mechanisms. Ageing information, wear tests and other functional parameters such as wear, friction, and absobtivity et al. are not readily available for RM.
- It is also important to realize that unlike metals, material properties in plastics can vary with section thickness, load rate and other factors as shown in previous experiments and works of authors cited in this chapter.

According to the scope of application of the RMADS system to assist in the process/materials selection for a machinery and industrial parts more information is needed regarding functional properties such as: wear, friction behaviour, resistance to solvents, acids, alkalis and performance under stress conditions and structural applications. Otherwise the mechanical basic properties shown by manufacturers will be of little help to gain the engineer trust for more demanding applications.

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Contents

9. Application of the RMADS system and case studies

Abstract

In this section a number of case studies are developed so that the use and functionality of the RMADS system can be illustrated. The sample parts correspond to real industrial and machinery parts being developed for different projects in which the use of Rapid Manufacturing as an real alternative was not envisaged. It is the purpose of these case studies to show the path to the correct analysis and assessment in different areas comprising early product development such as: generic PDS, costing assessment and materials selection.

The results generated by the RMADS system show the user when additive manufacturing is a reasonable option, and on the other hand, it also justifies the adoption of different technologies on a more analytic basis rather than the subjective analysis usually undertaken.

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9. Application of the RMADS system and case studies

9.1 Introduction

This chapter presents four different case studies where the functionalities of the newly developed RMADS system are assessed in order to evaluate its ability to identify new possibilities for Rapid Manufacturing processes. Specifically, these case studies describe four different machinery and special equipment parts whose analysis may lead to the assessment of Rapid Manufacturing processes as potential manufacturing routes. The final intention is to identify advantages due to cost, ease of fabrication or new material opportunities; therefore each case study is accompanied by a brief scenario description where the main functional requirements can be clearly stated. As shown in Figure 9.1, each case study includes: the final application, functional requirements, and when possible, the initial materials proposals and current cost of the conventional manufacturing method and its associated tooling.

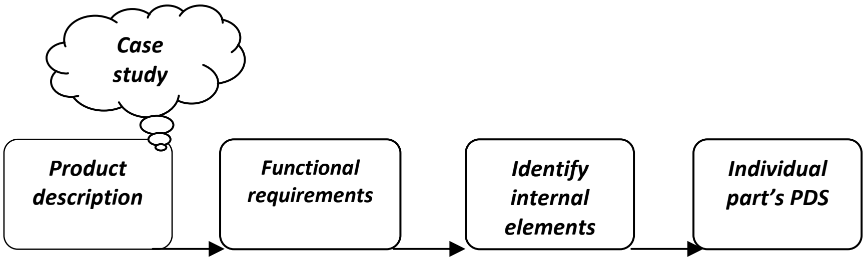


Figure 9. 1 Presentation of Case studies

From the four case studies, three were provided by the Machinery and Industrial Equipment Design Centre (CDEI-UPC) of the Technical University of Catalonia, who has facilitated the information, illustration and access to the actual components and equipment. Another case study was extracted from the TRIALPRO project, performed by the Spanish Rapid Manufacturing Association (ASERM, 2008) which is intended to investigate on the functional behavior of Rapid Manufactured parts under operating conditions.

The purpose of this section is to test the performance of the different modules that comprise the RMADS system, whether they are only partially or fully used. The results presented by the system's interface are intended to show the designer/engineer, potential options for the assessment of specific parts. The results expected from the different modules are:

- **Module 1**. General requirements: A qualitative ranking over the range [0-1] intended to show the feasibility of candidate RM technologies. While 0 would mean that the process is not suitable for the specified task, qualifications from 0 to 0.5 would mean relatively low suitability. A final ranking from 0.5 to 1 means that surviving RM options exhibit similar potential to other conventional manufacturing processes.
- **Module 2**. Cost comparison: A quantitative estimation of the cost per part for a user-defined batch size, and for the technologies selected by the user. On the one hand the system calculates individual part cost, and on the other hand it is possible to extend the calculations to low volume productions, obtaining a graphical representation.
- **Module 3**. Materials selection: A screened rank of suitable materials by filtering qualitative/quantitative parameters, and a graphic area for comparison of attributes of interest.

An overall scheme of the RMADS criteria is shown on Figure 9.2, which illustrates the iterative flow of parameter selection which can be altered anytime during the analysis.

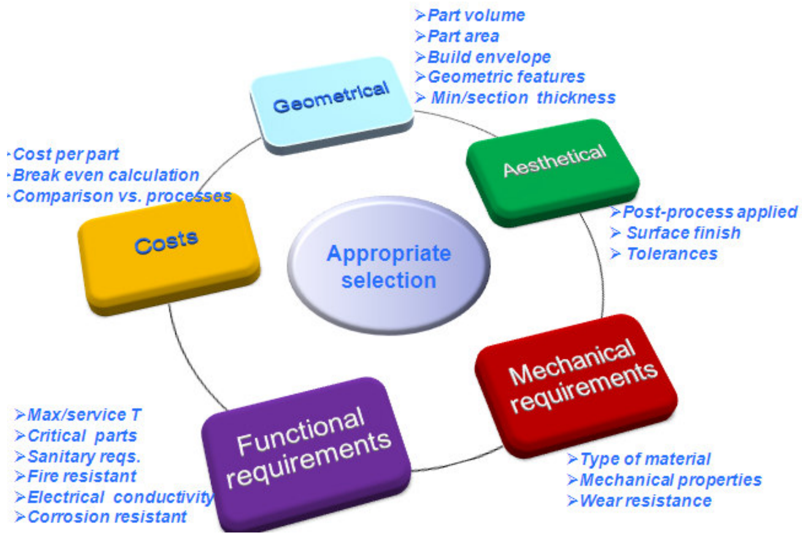


Figure 9. 2. General Scheme of the RMADS system (Munguía 2008)

Altogether, these modules are expected to show to the user, the advantages or drawbacks of using certain RM methods. Additionally they will show the options and parameters that may be changed in order to either, fit a given RM technology to the intended task, or rule it out definitely as an alternative.

9.2 Case Study 1. Muscle Relaxation Machine (MRM)

The Machinery and Industrial Equipment Design Centre (CDEI-UPC) received a request to design a special purpose machine for the relaxation of the leg's muscles to be used in Gyms and by professional athletes after training. The intention of this apparatus was to relax different zones of the legs by providing a sort of continuous automated massage. The design had to fulfill a number of special requirements such as:

- Low initial investment. As the prototype would be exhibited prior to getting manufacturing orders from potential buyers, it was required to obtain a one-of product, followed by short series production.
- Manufacturing processes should respond to rather low volumes.
- Modular architecture (easy to transport)
- Lightweight. The apparatus was conceived to be a movable object withing the exercising area therefore its weight was a crucial restriction.

The solution CDEI came up with is based on a repetitive linear motion applied in the zone of the ankles which is meant transmit a smooth shake-like movement to the rest of the body (CDEI 2008). The rotational movement is generated by an AC motor and then converted to linear motion by a connecting rod system, in what could be said a basic motion translation system.

The final proposed design is shown on Figure 9.3 in its definitive design Figure 9.3(right) with its internal elements. Figure 9.4 shows the MRM system in use with the primery position. It is possible to observe that most internal components are metallic, combined with standard elements such as screws, bolts and nuts. Most of the custom-made parts were intended for the sand casting and permanent mould casting processes due to their low cost of for small batches (in this case 300 units per year); however this manufacturing option represents collateral drawbacks such as an increase in the overall weight and necessary design restrictions that must be imposed in order to fulfill the sand casting process requirements.

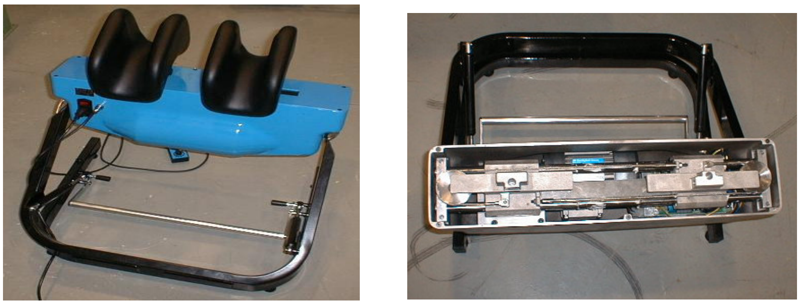


Figure 9. 3 The complete MRM design (left) and the top view with the internal metallic parts (right). Courtesy of CDEI

Figure 9. 4 The basic position of the proposed MRM system with variable inclination. Courtesy of CDEI

Some of the restrictions imposed by the mould Casting process that might influence the design of some internal parts include the following considerations:

Table 9. 1 Design restrictions of the mould casting process. (Boothroyd, Dewhurst et al. 1994)

Process	Usual geometrical constraints regarding part and design considerations
Metal Casting	• Requires projection of draft angles and Radius similar to wall thickness • Non difficult bodies are preferred in order to avoid the use of internal nucleus • Firmly hold the nucleus so to avoid unwanted displacements and the formation of walls with different thickness • Doesn't accept hidden or captured cavities. • Avoid sharp corners and angles as well as multiple union points • Consideration of metal shrinkage is necessary • Partition line must be projected on the most regular geometry section

Although the proposed design fulfilled the requirements imposed for the original Product Design Specifications (PDS), a number of design possibilities remained to be explored by the team, not being addressed due to development time restrictions (approximately 6 months). Some of these opportunities are:

- The exploration of alternative materials and processes, specially focused on internal components in order to achieve important weight reductions.
- The re-design possibilities allowed by potential RM methods in case they fulfil the most critical operating conditions.

The following cases illustrate the analysis performed on two internal components of the MRM system, intended to show possible advantages of using RM methods.

9.1.2 Connecting rod

Attached to the AC motor is the connecting rod (Figure 9.5), which is intended to transmit rotatory movement to the MRM system to be converted afterwards to a limited linear displacement. The original part designed by CDEI incorporates two parallel axes (through holes) one of them with a permanent guiding slot and hidden holes for adjusting screws. Due to economy of manufacture, the selected process for building the connecting rod was metal casting, as opposed to the machining process, it was possible to include up to 8 parts in the casting mold as shown in the figure below. However this selection is twofold; on the one hand the fabrication of low volumes is more cost-effective that machining, however for one-of parts the use of a mould produces a considerable increase in the part cost.

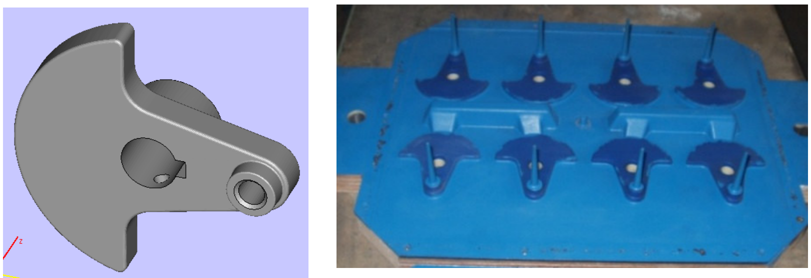


Figure 9. 5 3D model of the connecting rod (left) and casting mould with eight cavities (right). (courtesy of CDEI-UPC)

As provided by the CDEI centre the following table illustrates the main functional requirements comprising the PDS of the specific part. Some of this parameters such as dimensions and material requirements will be used as input information for the respective RMADS modules.

Table 9. 2 Design specifications for the connecting rod

	Material requirements:
•	Low material density (proposed material: Al-6063)
•	Moderate mechanical resistance
•	Average to rough surface finish (only the axis surface must be machined)
	Process requirements:
•	Good tolerances for internal geometrical features (provided by machining)
•	Lowest cost possible
	Geometry requirements:
•	Part Length: 91.02 mm
•	Part Width: 95.03 mm
•	Part height: 32.04 mm
•	Volume = 54937.57 mm^3
	Cost parameters
•	Metal casting mould: 1,250 €
•	Price per unit : 1.8 €
•	Price per batch 50 u = 90 € (8 parts per mould)

Before proceeding to fabritation, the CDEI team performed a series of 3D modeling and simulation test in order to evaluate the proposed geometry. From the analysis of the part and the stresses to withstand there were not major implications identified to comprimse the performance. Figure 9.6 shows the basic development cycle for this part.

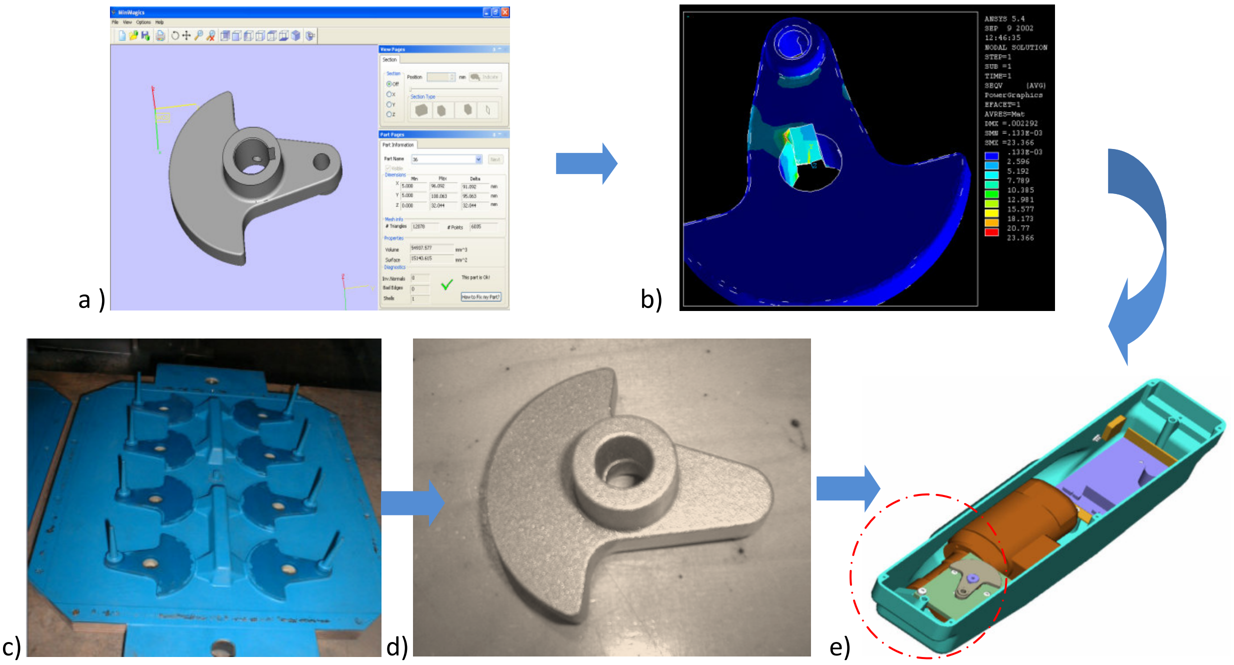


Figure 9. 6 Fabrication process for the Al-6063 connecting rod and it final assembly. a) CAD design, b) FEA analysis c) Metal casting process with multiple cavities d) Part finishing e) Assembly (courtesy of CDEI-UPC)

After the process was completed it was observed that the final part exhibits highly variable tolerances and slight geometry irregularities which are typical of the metal casting process. These irregularities are amended by post processing, however this cost and processing time shouldbe added to the final casting cost. After reviewing the overall design of the connecting rod, there are a number of issues that suggest that this internal part might be considered for further analysis:

- The process originally adopted may not be optimal for the production of one-of parts
- Nor is it appropriate for further design changes and modifications
- The metal casting process provides a rough surface, which can be improved by several RM methods
- The final element must be post-processed in order to be correctly assembled within the system

Therefore the connecting rod is analyzed using the RMADS system as illustrated in the following section.

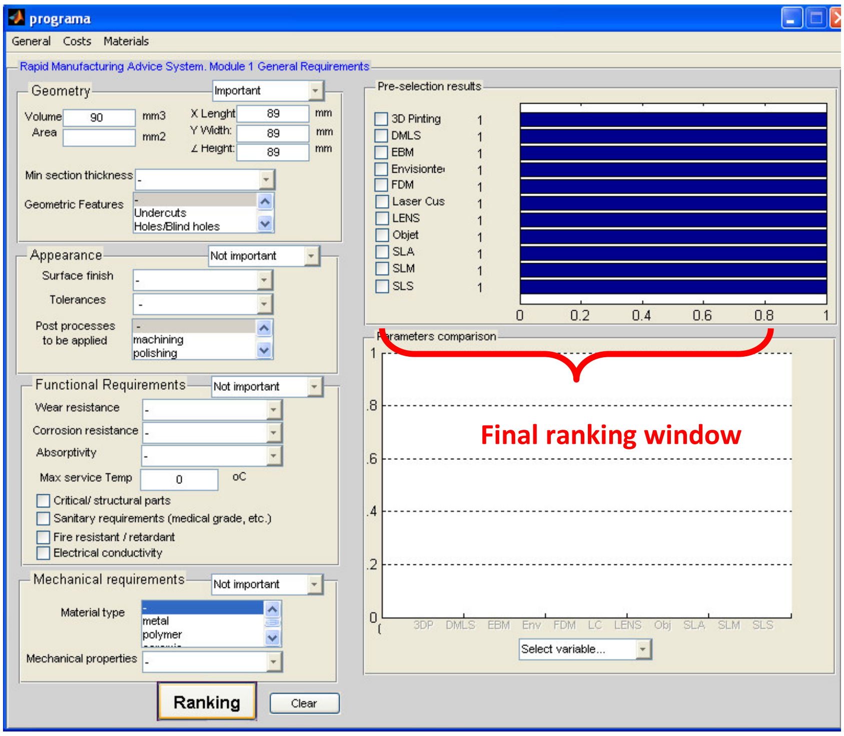
Deploying the RMADS system

As explained in previous chapters the RMADS system is comprised of three independent modules which can be executed separately regardless of the order as the individual results are not affected by the rest of the modules. It is the user who has the ‘last word’ after reviewing the results separately.

In the case of the connecting rod it is important to assure that some RM processes are capable of providing similar or even better performance, therefore the General requirements module will be first executed, followed by the costing module. As cost is an important parameter it will be considered before the materials module, as there are not material constraints imposed.

STEP 1. General requirements assessment

The figure below (Figure 9.7) shows the generic product requirements being entered in the main RMADS window. It is possible to observe how before making the parameter selection, all RM alternatives are ranked as feasible. This is shown in a scale from 0 to 1 in the upper right corner. As the selection of parameters continues, the resulting graph will tend to illustrate the changes in the overall performance of the candidates.



Geometry: Important
Volume: 90 mm3
Area: mm2
X Lenght: 89 mm
Y Width: 89 mm
Z Height: 89 mm
Min section thickness: -
Geometric Features: - / Undercuts / Holes/Blind holes

Appearance: Not important
Surface finish: -
Tolerances: -
Post processes to be applied: - / machining / polishing

Functional Requirements: Not important
Wear resistance: -
Corrosion resistance: -
Absorptivity: -
Max service Temp: 0 oC
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

Mechanical requirements: Not important
Material type: - / metal / polymer
Mechanical properties: -

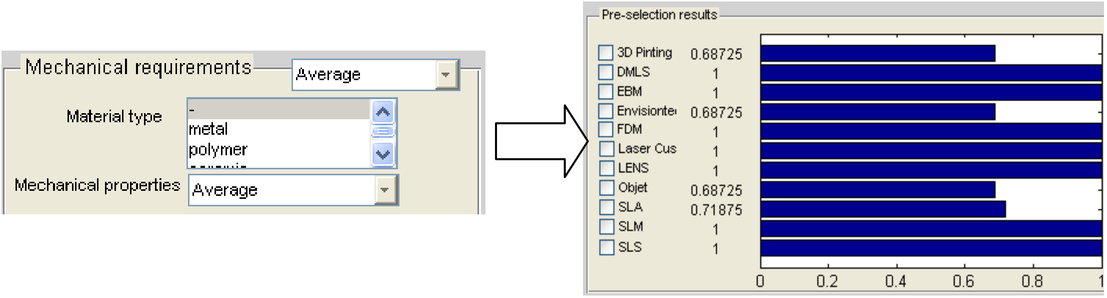
Pre-selection results

☐ 3D Pinting	1
☐ DMLS	1
☐ EBM	1
☐ Envisiontec	1
☐ FDM	1
☐ Laser Cus	1
☐ LENS	1
☐ Objet	1
☐ SLA	1
☐ SLM	1
☐ SLS	1

Figure 9. 7 RMADS Module 1. General Requirements

Acording to the functional requirements of the connecting rod, this information will be used as input data for the RMADS system. The next figures show the sequence of ranking generated during the selection of different parameters:

a) Mechanical requirements. While not specially demanding, the functionality of the overall system would require minimum-average properties. Although the original part was built in Aluminum this does not comprise a restriction, therefore the ***'Material type'*** option will be kept clear. In this case the material type is not restricted to metals. Also to be noted, the listbox at the upper right corner contains the ***'Importance factor'***. Each individual window contains this option which at the end of the selection defines the final ***'Importance vector'*** that has a major influence in the final ranking. As defined on Chapter 4 this vector is defined by linguistic terms which are then translated to fuzzy numbers. In this case the importance of the Mechanical requirements is considered ***'Average'***.



Mechanical requirements: Average
Material type: - / metal / polymer
Mechanical properties: Average

Pre-selection results

☐ 3D Pinting	0.68725
☐ DMLS	1
☐ EBM	1
☐ Envisiontec	0.68725
☐ FDM	1
☐ Laser Cus	1
☐ LENS	1
☐ Objet	0.68725
☐ SLA	0.71875
☐ SLM	1
☐ SLS	1

Figure 9. 8 RM process ranking resulting from the "Mechanical requirements" box

Functional requirements. The requirement that best defines the most likely cause of failure is ***'Wear resistance'***, as the connecting rod is intended to withstand an elevated number of cycles. Once set to ***'High'***, there is another parameter of interest that may affect the rod performance; that is the ***'maximum service temperature'*** due to the repetitive movement of the part.

The preliminary results shown on Figure 9.9 indicate that 3D printing and Objet processes are not suitable for this task. Although other relatively weak processes such as SLA survived this stage, it presents a lower performance index compared to the rest of the processes. It must be noted that the preliminary results in this stage are the aggregation of the results from the previous box.

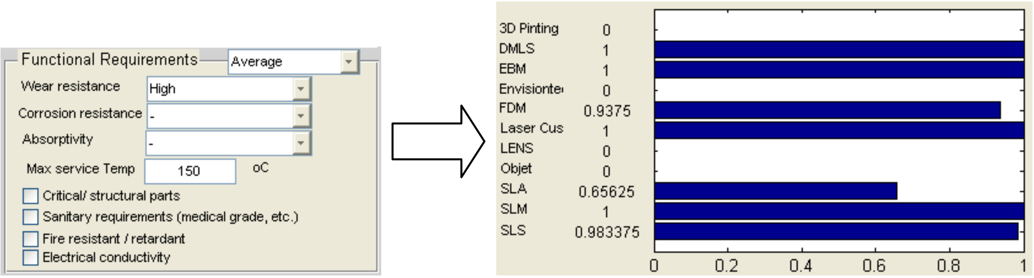
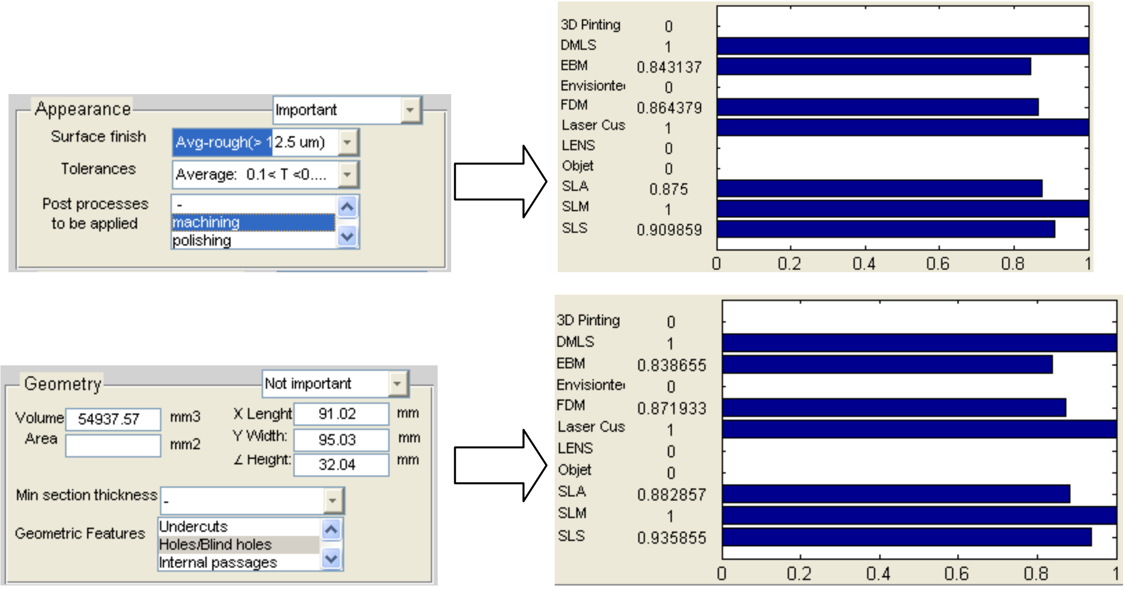

Functional Requirements: Average
Wear resistance: High
Corrosion resistance: -
Absorptivity: -
Max service Temp: 150 oC
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

Figure 9. 9 RM process ranking resulting from the "Functional requirements" box

The next box to be selected is ***'Appearance'***, comprised by the parameters: Surface finish, Toleraces and Post-processes. Although the connecting road is an internal part without aesthetical implications, the inner surface of the through-holes must be smooth enough to serve as a axis of rotation, therefore the Importance factor of the overall box is set to ***'Important'***.

On the other hand the ***'Geometry'*** box is set to ***'Not important'*** as there are minor implications with geometric constraints. Figure 9.10 shows the slight influence of ***'Appearance'*** and ***'Geometry'*** parameters on the final results due to the nature of the end function.


Appearance: Important
Surface finish: Avg-rough(> 12.5 um)
Tolerances: Average: 0.1< T <0....
Post processes to be applied: - / machining / polishing

Geometry: Not important
Volume: 54937.57 mm3
Area: mm2
X Lenght: 91.02 mm
Y Width: 95.03 mm
Z Height: 32.04 mm
Min section thickness: -
Geometric Features: Undercuts / Holes/Blind holes / Internal passages

Figure 9. 10 Influence of Geometrical and appearance parameters on the final ranking

As a result of this preliminary selection, most metallic processes appear to be feasible candidates while polymer-based methods are also feasible but to a lesser extent. This first stage seems useful for eliminating those RM processes with the lowest ranking however it does not provide yet a clear winner process.

Nevertheless this is intentional as the RMADS system is not intended to show a wining process, but to provide criteria for a more informed decision. Therefore the complementary information from other modules will be necessary.

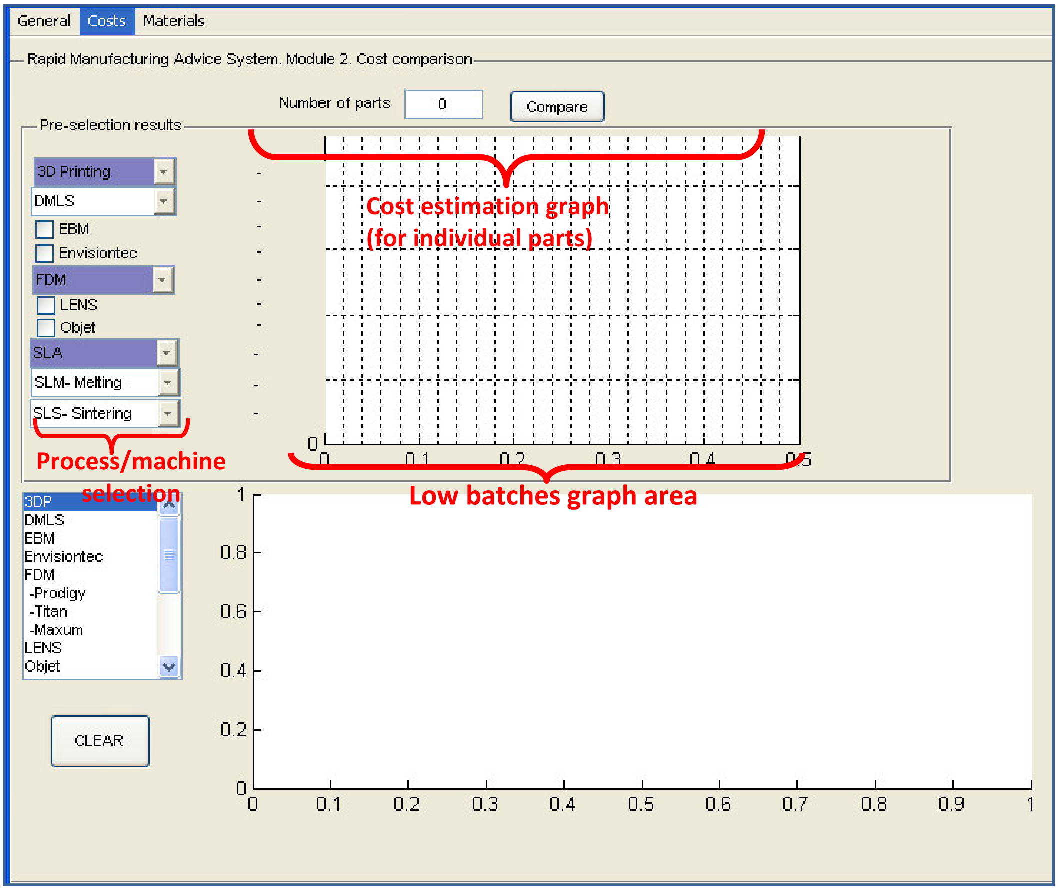
Step 2. Costing module

The Costing Module of the RMADS system (Figure 9.11) shows a number of RM processes with the option for selecting a specific machine model. For some processes such as DMLS, SLM and SLS the cost calculation is performed by means of ANNS as defined in Chapter 6, while for FDM and SLA the calculation is made using parametric methods as defined on Chapter 5. The rest of the processes (EBM, Envisiontec, LENS, Objet) are not yet linked to either type of cost calculation in this version. The aim of the RMADS system is to develop a more comprehensive database of ANN modeled processes however for the purpose of demonstration only three ANN models have been developed in this work.

The following image (Figure 9.11) illustrates the functionality of the Costing module. The two actions required from the user are:

1) introducing the number of parts to be estimated

2) Selecting the process and machine of interest.



Rapid Manufacturing Advice System. Module 2. Cost comparison

Number of parts: 0

Cost estimation graph (for individual parts)

Process/machine selection

Low batches graph area

Figure 9. 11 Main window of the costing module

When either of the DMLS, SLM or SLS processes are selected the system activates the ANN-based module which as a first step, performs the initialization and training of the respective Neural Networks(Figure 9.9).

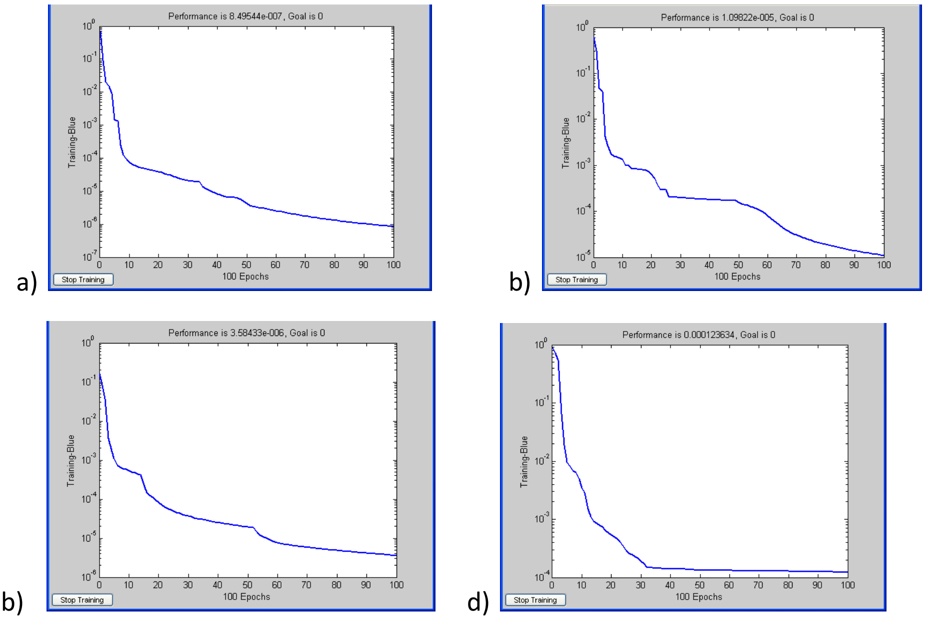
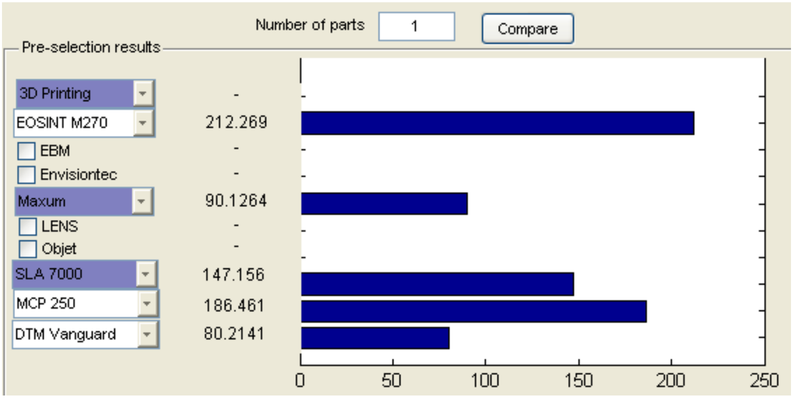


Figure 9. 12 Training graphs for the activated ANN models. a) DMLS, b) SLM concept M1 c) SLM MCP 250 d) SLS DTM Vanguard

The previous graphs show the performance of the ANN models regarding the training samples used to train the system. The geometrical information is taken from the previous Module and then used as '*simulation data'* by the Costing Module providing accurate estimates which range from 2 to 15% as shown in Chapter 6. In the case of the connecting rod, when the batch size is introduced as shown below (Figure 9.13), the system calculates the individual cost and plots it onto the bar graph. It is important to know that the individual part cost will vary according to the machine selected within the same RM process. This is due to differences in the build volume available, processing speed, laser power, etc.

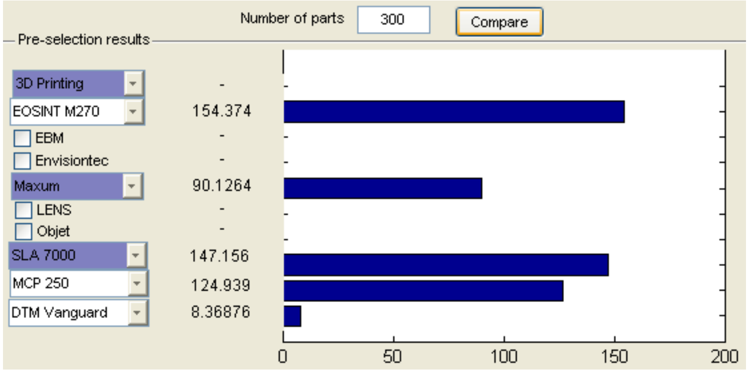

Number of parts: 1

Pre-selection results

3D Printing	-
EOSINT M270	212.269
☐ EBM	-
☐ Envisiontec	-
Maxum	90.1264
☐ LENS	-
☐ Objet	-
SLA 7000	147.156
MCP 250	186.461
DTM Vanguard	80.2141

Figure 9. 13 Part cost in Euros for different RM processes (X axis)

Since the product PDS specifies production volume of 300 units /year, this number is entered to the system showing the graph below. The results illustrate the effect of the cost calculation model followed. For instance if the part is quoted through an online service bureau for the SLS process with PA as material, the minimum price per part will not be lower than 110 Euros. However the calculations made by the RMADS system provide a much lower cost (8,36 €). The explanation is that the model considers the machine for dedicated production, dividing the total material costs, manufacturing and administrative overheads by the total number of parts being constructed. Again, the system is not intended to calculate the commercial price but the actual cost of building a given part on the selected method.



Number of parts 300

Pre-selection results

3D Printing	-
EOSINT M270	154.374
☐ EBM	-
☐ Envisiontec	-
Maxum	90.1264
☐ LENS	-
☐ Objet	-
SLA 7000	147.156
MCP 250	124.939
DTM Vanguard	8.36876

Figure 9. 14 Cost per part corresponding to a 300 units batch

The lower part of Cost Module screen shows a series of graphs for the extended part cost, i.e. they tend to show the evolution of part cost compared with an increase on the batch size. The characteristic curve corresponds to the saw-like shaped curve described by (Ruffo, Tuck et al. 2006). This curve shows the effect of filling up each individual batch for production until, with a sufficient increase in the production volume, it is possible fill the complete machine vat, thus considerably reducing the part cost.

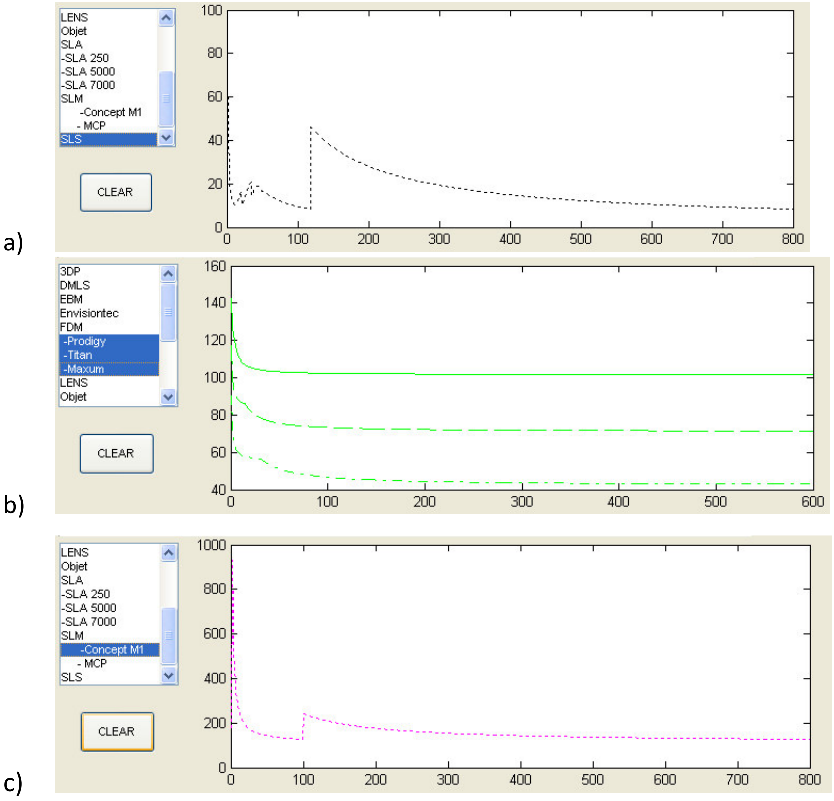


Figure 9. 15 Extended costing graphs for the technologies selected on the Combo-box a) SLS, b) FDM, c) SLM

With the above illustrated graphs it is possible to stablish a comparison between Rapid Manufacturing processes and other manufacturing routes, as long as these cost are available. In the case study of the connecting rod, information about manufacturing costs of the metal casting process are being provided, thus it will be possible to perform such comparison by creating a break-even curve (Figure 9.16).

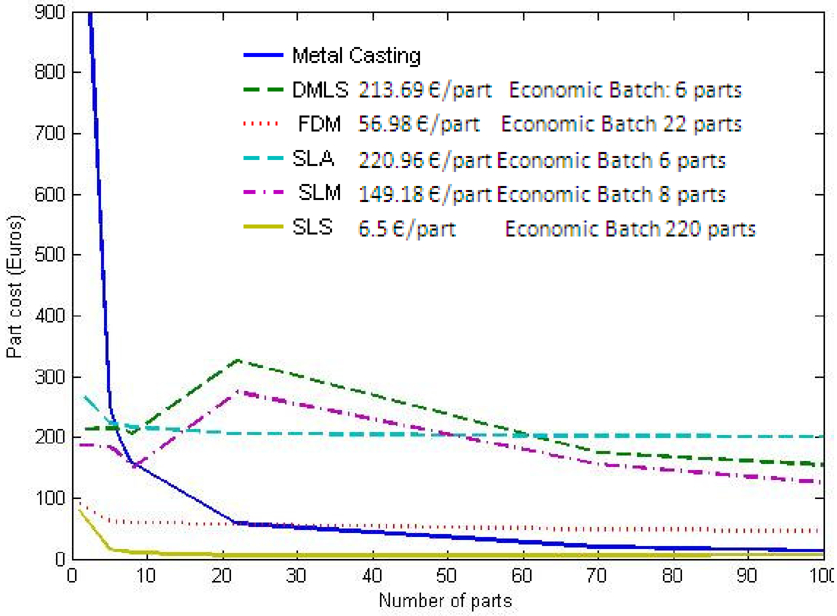


Figure 9. 16 Break-even curve for RM technologies vs. Metal casting

From this graph it is clear that no RM alternative provides a cost effective solution regardless of their technical capability, therefore the materials module will not be executed since it has been proved that the maximum number of parts that can be economically fabricated is 220 (with the SLS process) which is not enough to accomplish the required production volumes. Permanent mould casting seems to be more cost-effective especially due to the capability of providing multiple cores. The next example shows another metallic part without the advantage of multiple cavities in one mould.

9.2.2 Moving block

The moving block is another important part of the MRM machine. Opposite to the connecting rod which performs a critical function, this part is a secondary element which might be investigated in the search of design opportunities. The moving block is a multi-functional part within the system as it is in charge of receiving (indirectly) the movement from the motor. It provides linear motion and acts as receptacle for the user's ankles. This part was also designed as a metallic part due to the cost effectiveness of the metal casting process for low batches. However some complications arose: it includes a series of through holes, overhangs and hollow features; hence it must contain a number of moving nucleus during the casting process which adds variable tolerances and low repeatability to the final parts. As a result of the process' influence, the definitive design had to be modified in order to fulfill with its restrictions. Figure 9.17 shows the initial design and the definitive shape altered by the casting process restrictions respectively.

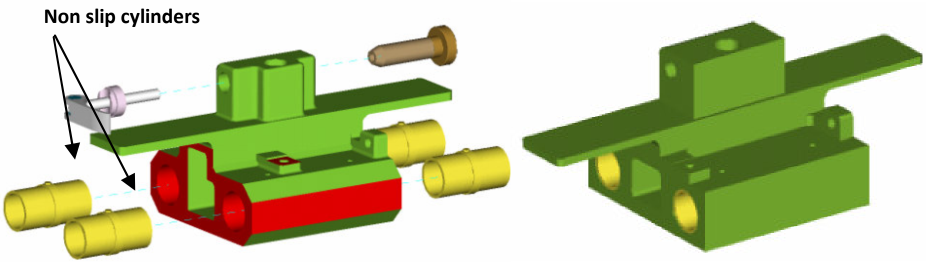


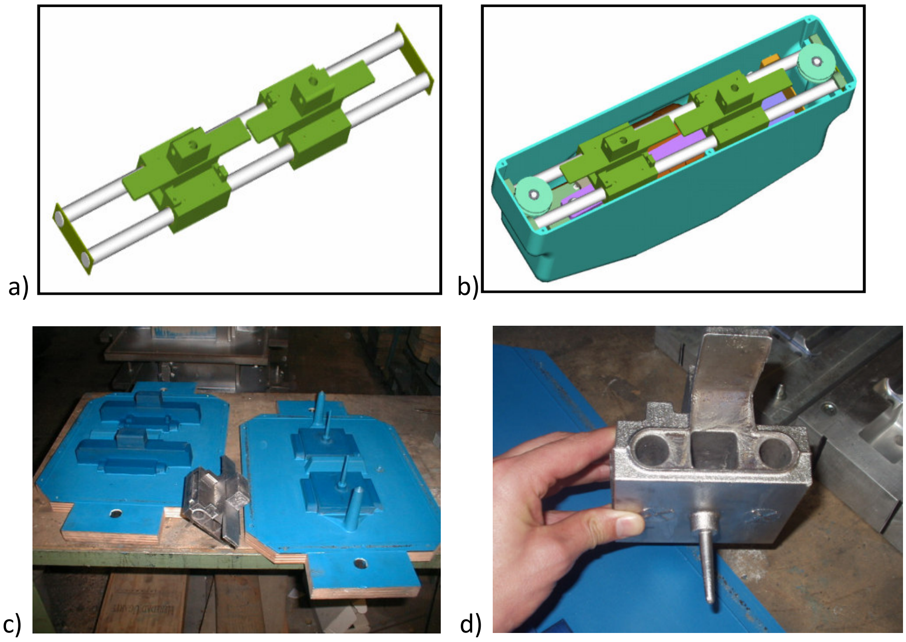
Figure 9. 17. The originally intended moving block and its interaction with its different elements(left) and the modified design that incorporates simpler and more basic features to be effectively casted (right) (courtesy of CDEI-UPC)

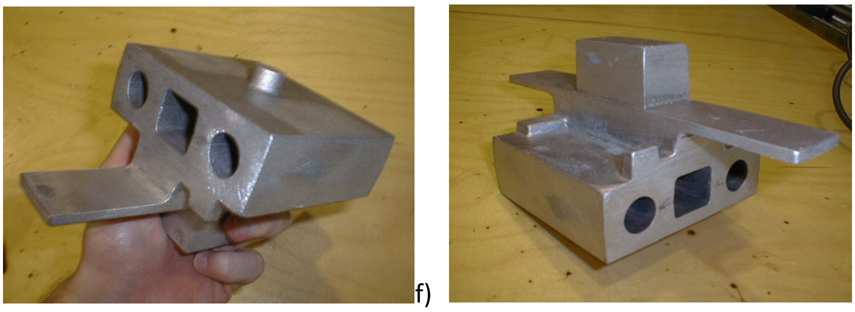
Similarly to the connecting rod there is information available for the moving block regarding materials, process requirements, geometrical and cost parameters. This info will be used as input data for the different modules of the RMADS system.

Table 9. 3 Initial PDS for the moving block

	Material requirements:
•	Low material density (proposed material: Al-6063)
•	Moderate mechanical resistance
•	Average to rough surface finish (only the axis surface must be machined)
	Process requirements:
•	Good tolerances for internal geometrical features (provided by machining)
•	Lowest cost possible
	Geometry requirements:
•	Part Length: 236.925 mm
•	Part Width: 110.966 mm
•	Part height: 105.113 mm
•	Volume = 382874.83 mm^3
	Cost parameters
•	Metal casting mould: 2,400 €
•	Price per unit : 8.9 €
•	Price per batch 100 u = 980 € (2 parts per mould)

The annual production of the MRM product is expected to be around 300 units per year, split in batches of 50 units, however every machine includes two moving blocks therefore the batch considered is 100 units. The design and production cycle of the moving blocks is illustrated on Figure 9.16.





e) f)

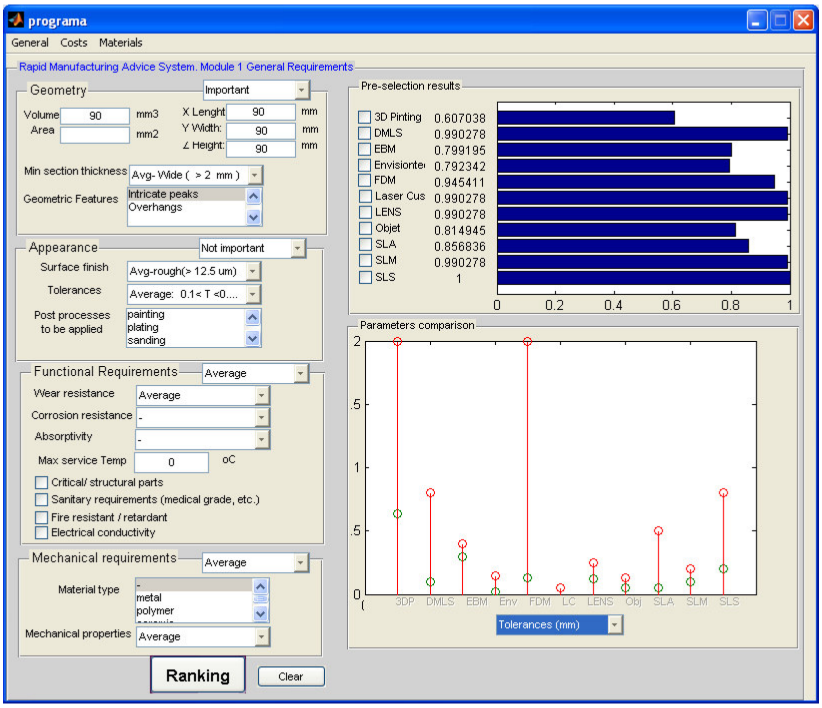
Figure 9. 18 Different stages of the development of the moving block. a) Dynamic simulation of the assembly. b) Virtual product mock-up. c) Mould design and metal casting process. d) Extraction of the final part. e) Part machined to remove unwanted material. f) Final part ready to be assembled. (courtesy of CDEI-UPC)

As it can be observed the casting process for the moving block also permits multiple cavities, however due to the part's size the maximum number is two. From the previous description it is possible to identify a number of issues that may lead to a search of alternative manufacturing options. For instance, the original design had to be modified by removing more intricate geometry thus reducing functionality. Also, due to the nature of the casting process it is not possible to build closed-hollow shapes, thus resulting in a heavier part without an optimum shape. In addition, the solidified extra material that must be removed creates the need for additional operations that will add an extra cost not considered in the final casted part cost.

Therefore the feasibility of using a given Rapid Manufacturing process for this part will be assessed following similar steps as in the previous case.

Step 1. General requirements module

The General Requirements module is not specially demanding regarding the feasibility of the moving block for RM. If the four main boxes are analized only the ***'Geometry'*** box may be assigned the importance attribute of ***'Important'***. The rest of the boxes are not crucial for the success of the part; for instance the ***'Appearance'*** box was selected as ***'Not important'*** while the ***'Functional requirements'*** and ***'Mechanical Properties'*** boxes were given an importance factor ***'Average'***.



Rapid Manufacturing Advice System. Module 1 General Requirements

Geometry: Important
Volume: 90 mm3
Area: mm2
X Lenght: 90 mm
Y Width: 90 mm
Z Height: 90 mm
Min section thickness: Avg- Wide (> 2 mm)
Geometric Features: Intricate peaks, Overhangs

Appearance: Not important
Surface finish: Avg-rough(> 12.5 um)
Tolerances: Average: 0.1< T <0....
Post processes to be applied: painting, plating, sanding

Functional Requirements: Average
Wear resistance: Average
Corrosion resistance: -
Absorptivity: -
Max service Temp: 0 oC
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

Mechanical requirements: Average
Material type: -, metal, polymer
Mechanical properties: Average

Pre-selection results

☐ 3D Pinting	0.607038
☐ DMLS	0.990278
☐ EBM	0.799195
☐ Envisionte	0.792342
☐ FDM	0.945411
☐ Laser Cus	0.990278
☐ LENS	0.990278
☐ Objet	0.814945
☐ SLA	0.856836
☐ SLM	0.990278
☐ SLS	1

Tolerances (mm)

Figure 9. 19 Final screenshot for the RMADS general requirements module

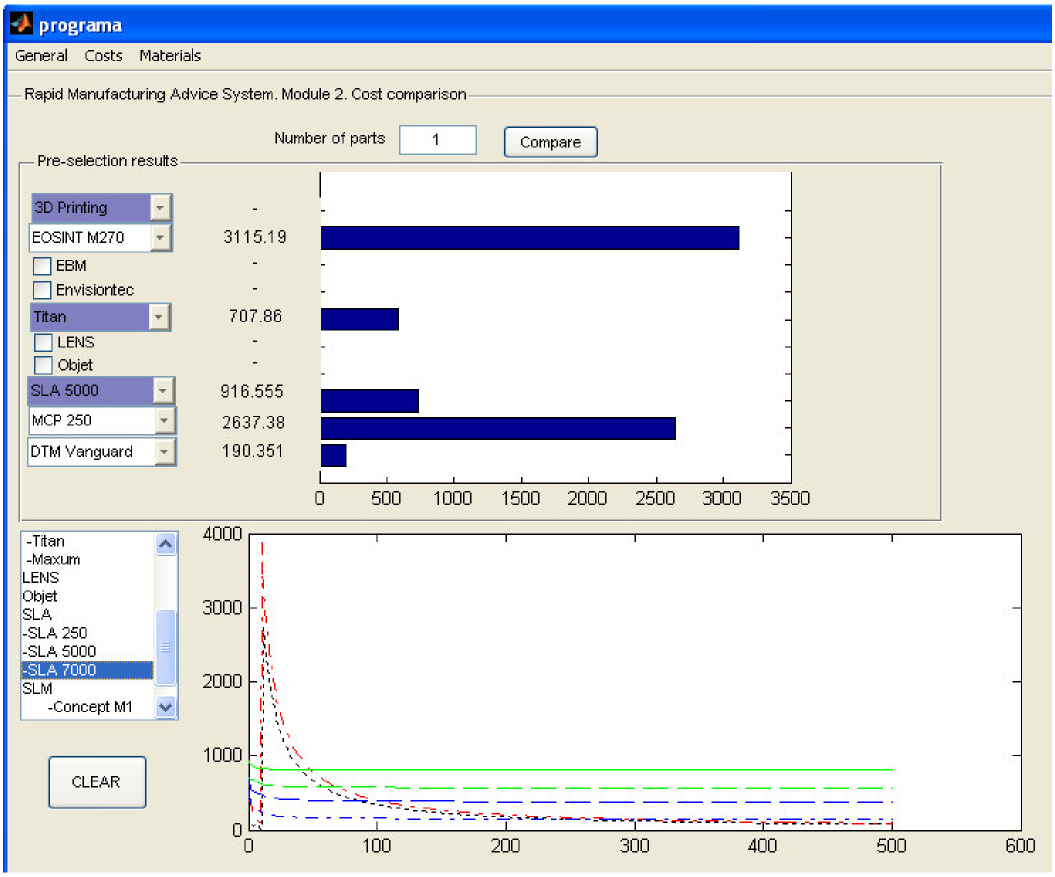
The following screen-capture (Figure 9.20) shows the results provided by the RMADS system for the general design requirements module. From the previous figure it is possible to observe how some parameters do not need to be activated such as: ***'Corrossion resistance', 'Absorptivity'***, ***'Max service temperature'*** and the combo of *critical multipliers* (Functional requirements box). The results show how most of the available RM alternatives seem feasible, with the exception of 3D printing that has the handicap of having low functional capabilities. Some of the processes who got the best ranking include mostly metal based technologies: DMLS, Laser Cusing, LENS and SLM.

At the right bottom of the screen capture it is possible to observe a comparison graph showing the Tolerance property for the studied RM processes. This can be seen as an additional tool for selecting the best option appealing to the designer's criteria. For instance, although the 3DP and FDM processes were not completely ruled out, by considering this graph it can be stated that the Tolerance levels provided by those processes are not good enough for the task.

Step 2. Costing module

The menu located at the upper screen allows selecting different processes and the machines currently available, i.e. the ones already modeled or simulated with ANNs or parametric method. The internal cost-calculations are made by extracting the part volume and, X Y, Z measurements from the previous Module. The results for a single part are shown on Figure 9.21.

It is possible to see how the DMLS and SLM do not meet the minimum cost requirements to be competitive versus metal casting, while the rest of the processes exhibit also high manufacturing costs which should be compared by a break-even graph against the metal casting process.



programa

Rapid Manufacturing Advice System. Module 2. Cost comparison

Number of parts: 1

Pre-selection results

3D Printing	-
EOSINT M270	3115.19
☐ EBM	-
☐ Envisiontec	-
Titan	707.86
☐ LENS	-
☐ Objet	-
SLA 5000	916.555
MCP 250	2637.38
DTM Vanguard	190.351

Figure 9. 20 Screen capture of the RMADS costing module with the individual part-cost estimation and the low batches graph.

The next break-even graph shows the disadvantages of using Rapid Manufacturing methods for the case study of the moving block, as the minimum economic batch does not meet the minimum production volume of 300 units specified for the MRM machine. Only in the cases when unitary parts or lower batches are programmed may RM be a feasible option for production.

These results however, give room to redesign alternatives. Munguía et. Al (2007) (see publication Annex) depicted a redesign analysis for a number of parts treated in this chapter including the moving block. In this analysis, a re-design of the linear movement mechanism of the MRM machine, leads to the development of smaller and lighter parts with different dimensions which may be suited for additive production. Consider the part shown on Figure 9.23 which is the substitute of the moving block for a hypothetical re-design of the MRM machine.

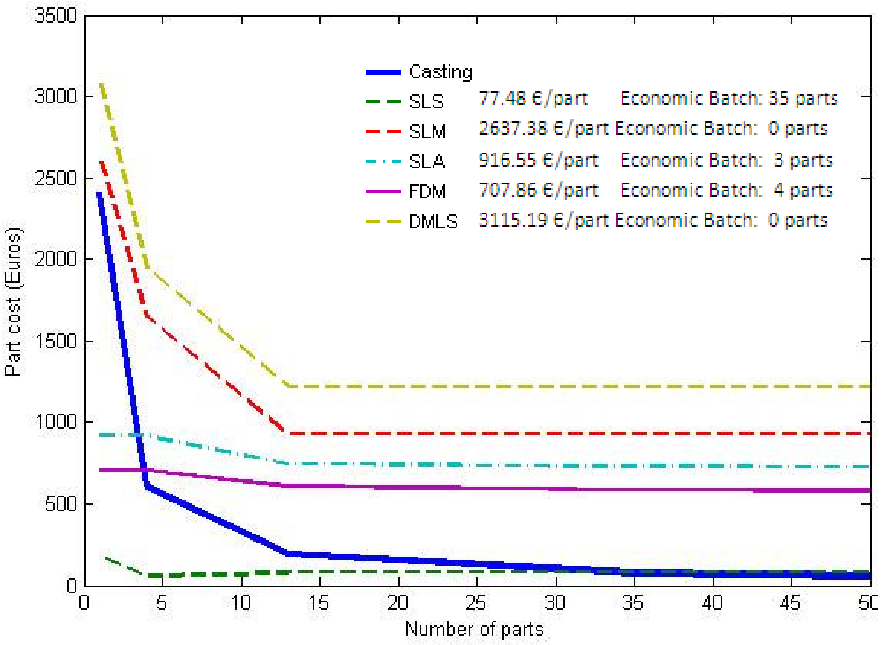
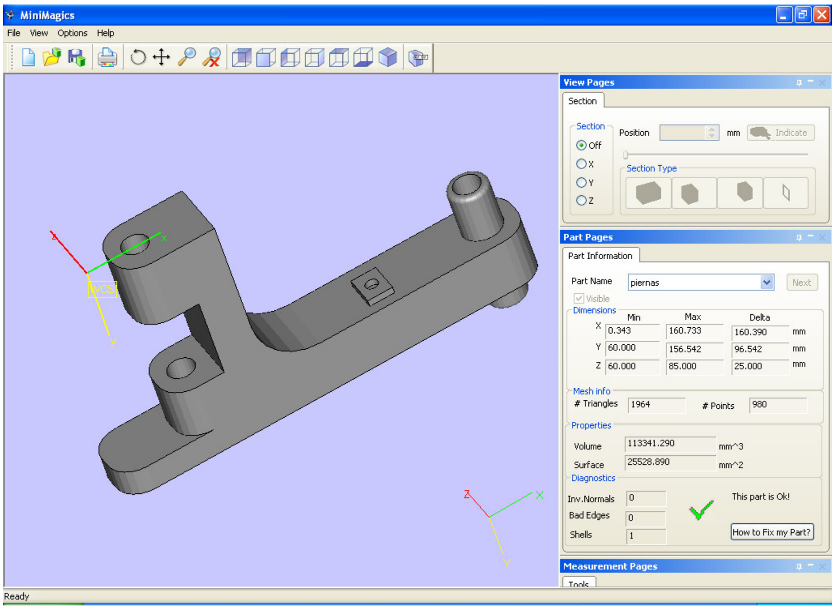


Figure 9. 21 Break-even curves of RM technologies vs. Casting process



Section: ● Off ○ X ○ Y ○ Z

Part Name: piernas

☑ Visible

Dimensions

	Min	Max	Delta	
X	0.343	160.733	160.390	mm
Y	60.000	156.542	96.542	mm
Z	60.000	85.000	25.000	mm

Mesh info

Triangles: 1964
Points: 980

Properties

Volume: 113341.290 mm^3
Surface: 25528.890 mm^2

Diagnostics

Inv.Normals: 0
Bad Edges: 0
Shells: 1

✓ This part is Ok!

How to Fix my Part?

Figure 9. 22 Proposed internal part viewed on the Magics application. (Munguía et.al.,2007)

Since the functional requirements and operating conditions remain the same, for the newly designed and the previous version of the moving block, only the corresponding measures will be replaced, then the RMADs costing module is directly applied.

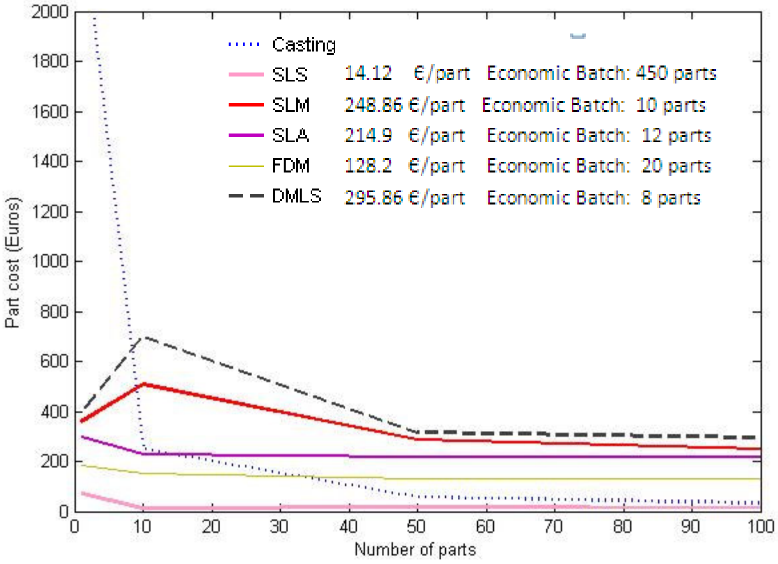


Figure 9. 23 Break-even curves of RM technologies vs. Casting process for the Modified part

From the previous analysis there are two issues that may be highlighted:

- The most cost-effective prediction method for RM is Selective Laser sintering, specially for bigger sized parts
- When RM does not provide economically feasible options, and the studied part is prone to be optimized and redesigned, there is usually room for improvement.

In this second case SLS presents a break-even point of around 450 parts which is enough for one year production thus in case the proposed re-design is adopted that would be a feasible manufacturing option, however as the analysis should be performed on the original moving block, the final decision will exclude RM as possible alternative for manufacture.

9.3 Case Study 2. Composite clutch pedal

This case study corresponds to a clutch pedal designed by the Automotive Technology Centre of Galicia (CTAG) within the TRIALPRO project (ASERM, 2008). The purpose of this project was to select mechanical parts with complex geometries and demanding functional requirements to be produced by a given RM technology, being the clutch pedal one of the test samples. As a result of this project a number of specimens for mechanical testing were produced and mounted into a test workbench. The RM process specifically used was Selective Laser Sintering as it was chosen on the basis of material suitability (Polyamide) and part size; however no analysis were performed on costing options and price comparison versus alternative metal techniques, therefore these issues will be addressed by this case study.

The clutch pedal consists of a lever that is cranked backwards from an upper end (boss) to its lower end, i.e. an enlarged foot pad. A through-hole in the boss is lined by a polymeric bush. The clutch pedal is pivoted in the clutch pedal location in the mounting bracket between the parallel gussets. A bolt, serving as a pivot-pin, and passing through the bush in the boss of the clutch pedal. It provides the pivotal connection to the location, being secured by a lock nut. The 3D solid model is shown along with its bounding box dimensions in Figure 9.22.

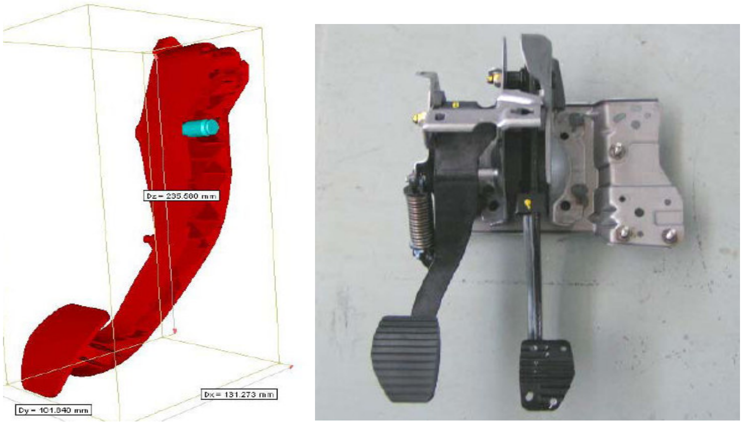


Figure 9. 24 Design of the CLutch pedal (left) and mounted element on the sheet metal case (right). Source: TRIALPRO project, (ASERM, 2008)

Instead of being made of steel alloys the clutch pedal design is optimized for composite materials with the injection molding process in mind. Some of the advantages of replacing isotropic-homogeneous steel alloys with reinforced polymers include: significant weight savings, optimized mould design and part performance (Sapuan, 2005). However more issues arise, related to material flow analysis and product costing.

The main requirements for the design of generic clutch pedals have been obtained from the product PDS and design recommendations listed by Sapuan (2005) for a similar case:

Material requirements:

- **Real material: PA66 + 30GF (similar properties)**
- **High corrosion resistance**
- **Low water absorption**
- **High mechanical resistance**
- **High modulus of elasticity**
- **Low material density**

Process requirements:

- **Tolerance for fitting with the sheet metal and bearing elements (Figure 9.22)**
- **Lowest cost possible**
- **Good dimensional stability**

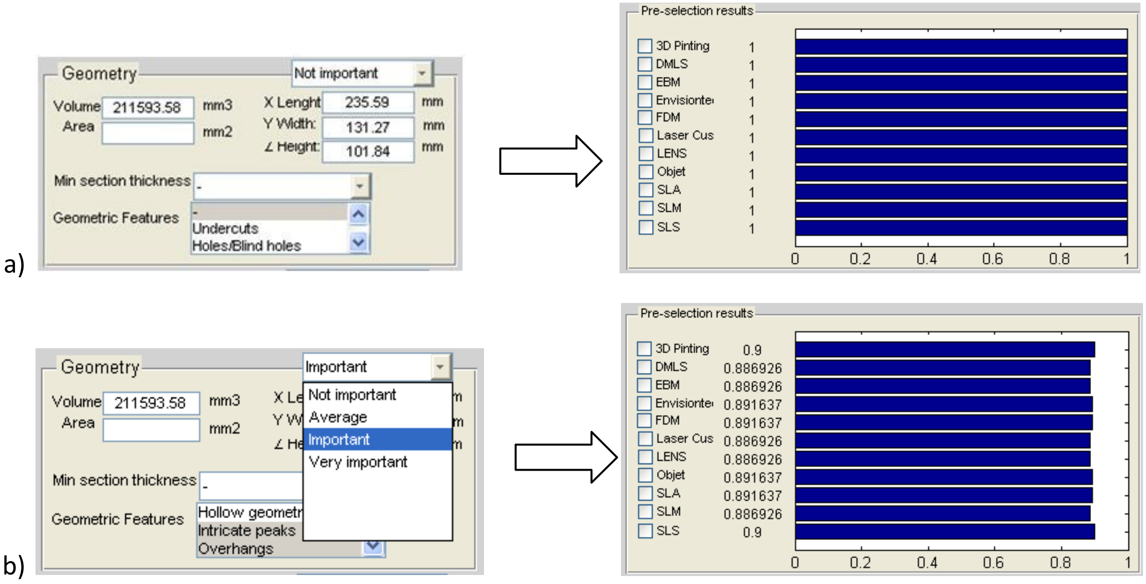
Geometry requirements:

- **Part Length: 235.59mm**
- **Part Width: 131.27mm**
- **Part height: 101.84mm**
- **Volume = 211 593.58mm^3**

Other geometrical features of interest that are present in the current design are: variable wall thicknesses, ribbings, contours and corrugation are desirable. The objective of this case study is to explore the suitability of RM methods for making this part considering the desired part requirements.

9.3.1 STEP 1. General design requirements (Module 1)

The clutch pedal dimensions are introduced as a first step into the ***'Geometry'*** box in order to determine whether the available RM equipment is capable of producing the part in a single piece or it must be divided in sections. The results show the suitability of all methods represented in a scale from 0 to 1 (Figure 9.26 a). This measure is not a quantitative ranking, but a qualitative indicator of suitability used throughout the system. Attending the geometric design requirements, the part is likely to contain ribbings and contours, besides a series of trough-holes to contain pivot pins, as well as a structure for holding springs and other standard components. These geometric features will be selected, and the importance factor is set to ***'Important'***, showing the results illustrated in Figure 9.26.



a)

Geometry: Not important
Volume 211593.58 mm3
Area mm2
X Lenght 235.59 mm
Y Width: 131.27 mm
Z Height: 101.84 mm
Min section thickness -
Geometric Features: -, Undercuts, Holes/Blind holes

Pre-selection results
☐ 3D Pinting 1
☐ DMLS 1
☐ EBM 1
☐ Envisionte 1
☐ FDM 1
☐ Laser Cus 1
☐ LENS 1
☐ Objet 1
☐ SLA 1
☐ SLM 1
☐ SLS 1

b)

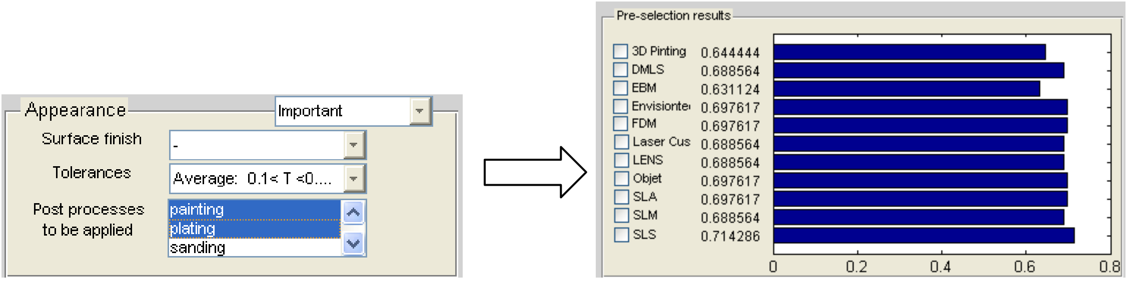
Geometry: Important (Not important, Average, Important, Very important)
Volume 211593.58 mm3
Area mm2
Min section thickness -
Geometric Features: Hollow geometr, Intricate peaks, Overhangs

Pre-selection results
☐ 3D Pinting 0.9
☐ DMLS 0.886926
☐ EBM 0.886926
☐ Envisionte 0.891637
☐ FDM 0.891637
☐ Laser Cus 0.886926
☐ LENS 0.886926
☐ Objet 0.891637
☐ SLA 0.891637
☐ SLM 0.886926
☐ SLS 0.9

Figure 9. 25 Differences on the final ranking due to parameter changes

The selection of different items of the ***'Geometric Features'*** listbox will affect the overall performance of the RM processes that require the use of support structures. As illustrated on Chapter 2, support structures usually imply secondary stage of removal and finishing which affects specially to metal based technologies. The option ***'Important'*** is selected from the Importance attribute Listbox, hence highlight the importance of such features for the final design.

The next parameters to be selected include ***'Tolerances'*** and ***'Post-processes'*** in the ***'Appearance'*** box. For tolerance the Average grade is selected (0.1< T <0.25 mm) as it is considered enough for the application. In the case of Pst-processes, since the final part is expected to operate in variable and demanding environments it will be likely to be painted and recoated by subsequent operations; these items will be selected from the menu. As both parameters are desirable but not critical, the Importance attribute selected will be ***'Important'*** showing the following result (Figure 9.27).

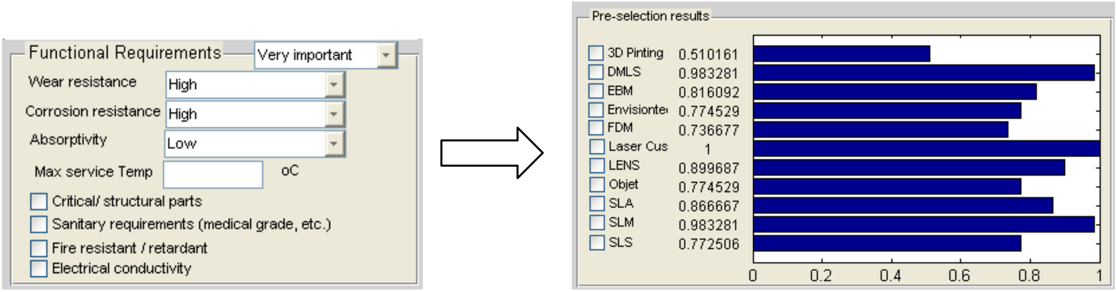


Appearance: Important
Surface finish -
Tolerances Average: 0.1< T <0....
Post processes to be applied: painting, plating, sanding

Pre-selection results
☐ 3D Pinting 0.644444
☐ DMLS 0.688564
☐ EBM 0.631124
☐ Envisionte 0.697617
☐ FDM 0.697617
☐ Laser Cus 0.688564
☐ LENS 0.688564
☐ Objet 0.697617
☐ SLA 0.697617
☐ SLM 0.688564
☐ SLS 0.714286

Figure 9.26 Changes of the final ranking affected by the Appearance box

Functional requirements regarding materials properties seem to be critical for the clutch pedal. The following figure shows the selection of the corresponding properties and the significative drop in the ranking of the least convenient processes such as 3D printing. This is caused by the ***'Wear resistance'*** and ***'Corrosion resistance'*** that are set to ***'High'***, while the Absorptivity is also kept to its optimum level (***'Low'***).



Functional Requirements: Very important

Wear resistance: High

Corrosion resistance: High

Absorptivity: Low

Max service Temp: oC

☐ Critical/ structural parts

☐ Sanitary requirements (medical grade, etc.)

☐ Fire resistant / retardant

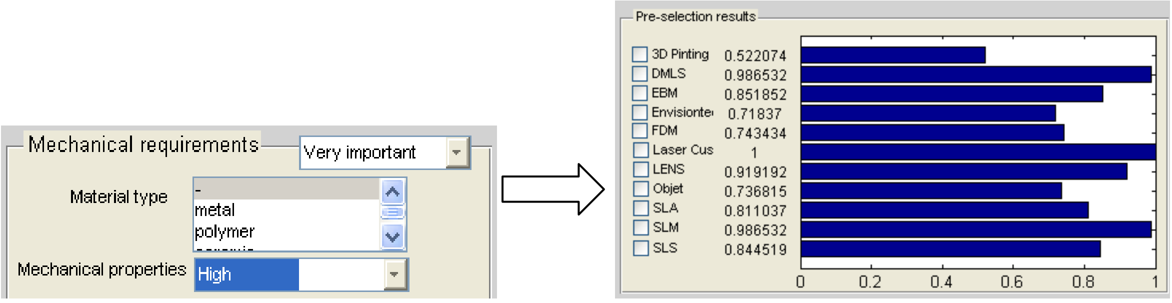
☐ Electrical conductivity

Pre-selection results

☐ 3D Pinting	0.510161
☐ DMLS	0.983281
☐ EBM	0.816092
☐ Envisionte	0.774529
☐ FDM	0.736677
☐ Laser Cus	1
☐ LENS	0.899687
☐ Objet	0.774529
☐ SLA	0.866667
☐ SLM	0.983281
☐ SLS	0.772506

Figure 9. 27 Changes of the final ranking affected by the Functional Requirements box

The above screenshot (Figure 9.28) does not include the screening case when temperature or criticality factors must be considered; as they are not specified in the initial PDS these options will remain unaltered, however there is a special emphasis on the high mechanical resistance needed for the final part. To this respect, the next box to be activated is the ***'Mechanical Requirements'*** where the Material type menu remains unrestricted but the ***'Mechanical properties'*** parameter is set to *'High'*. In this case the importance factor will be set to ***'Very important'*** (Figure 9.29) as this parameters might dictacte the suitability of the RM technologies for the given task.



Mechanical requirements: Very important

Material type: -, metal, polymer

Mechanical properties: High

Pre-selection results

☐ 3D Pinting	0.522074
☐ DMLS	0.986532
☐ EBM	0.851852
☐ Envisionte	0.71837
☐ FDM	0.743434
☐ Laser Cus	1
☐ LENS	0.919192
☐ Objet	0.736815
☐ SLA	0.811037
☐ SLM	0.986532
☐ SLS	0.844519

Figure 9. 28 Changes of the final ranking affected by the Mechanical requirements box

The final ranking shown on Figure 9.28 is the aggregate of all the previous rankings, i.e. the sum and normalization of the resulting vectors from each individual parameter selection. Although there seems to be a small difference between the above figures, there is a significative change in the capacities of a number of processes. For instance it is possible to observe how the EBM process is given a higher rank compared to Envisiontec when Mechanical properties are set "High". The same happens between LENS and Objet, thus showing the utility of fuzzy logic behind the user interface.

The General requirements module however does not specify a clear winner. Nor is it intended to do so, therefore it is appropriate to switch to the Materials module to specify the parameters of interest and get more specific results.

9.3.2 Step 2. The materials selection module

The main window of the Materials selection module (Figure 9.29) shows a number of basic properties such as Wear resistance, Corrosion resistance, absorptivity besides four checkboxes related to critical requirements. By enabling these options the candidate materials list is screened and reduced from the initial materials collection.

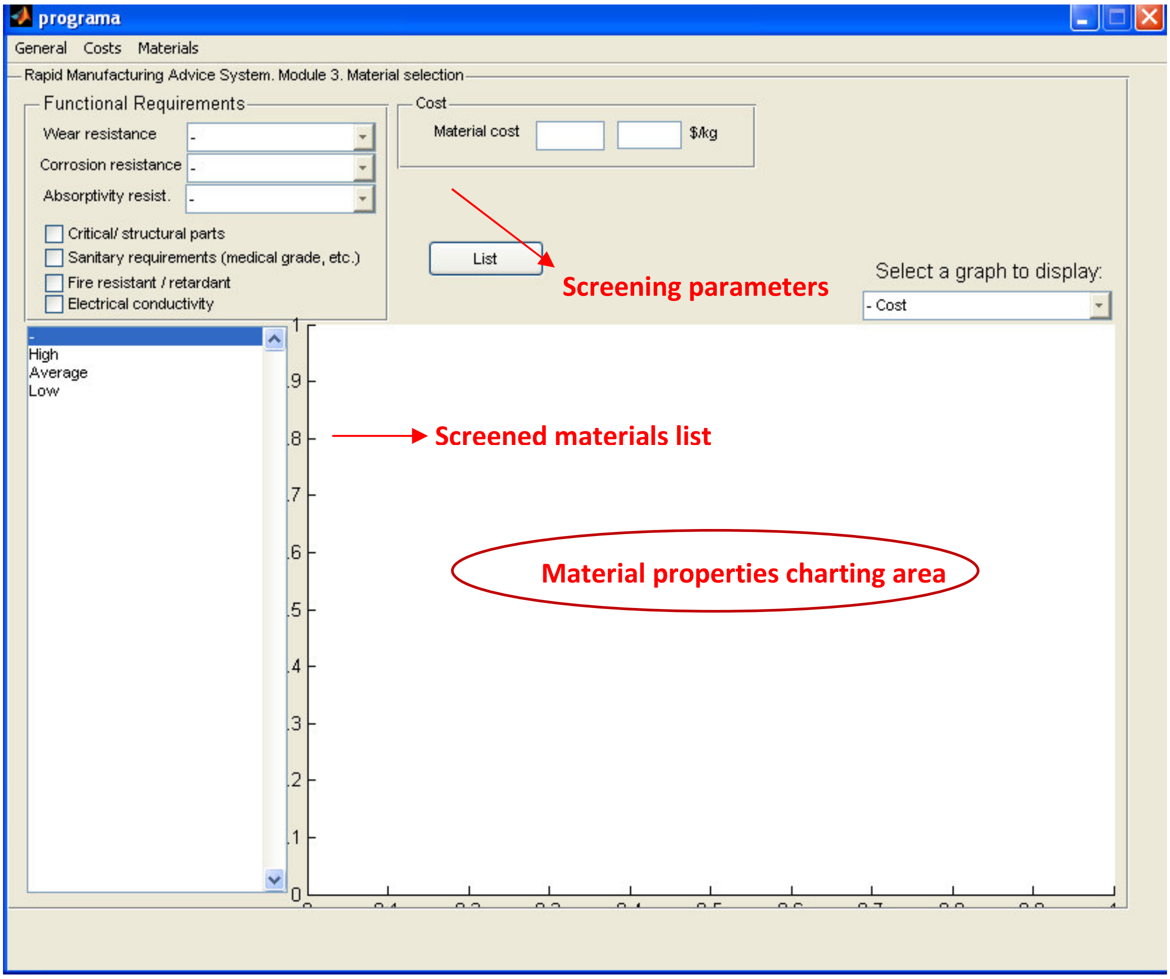
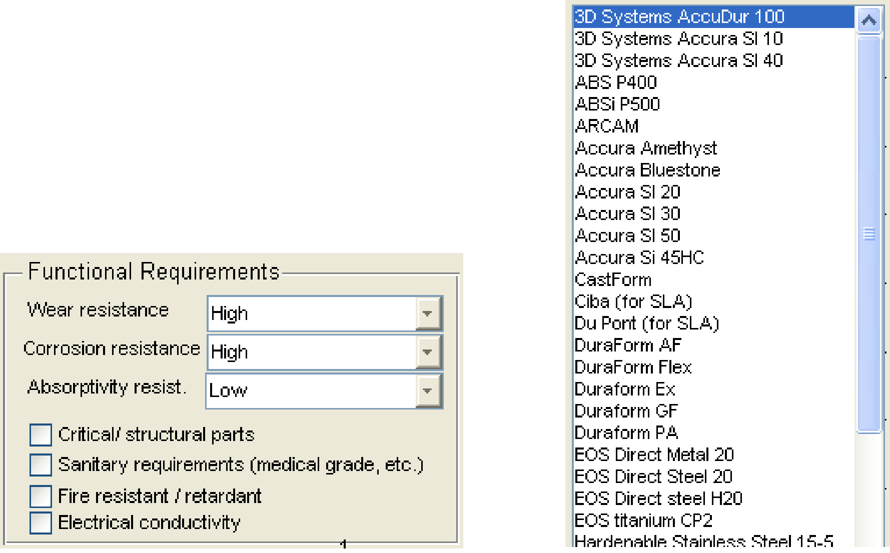


Figure 9.29 Screencapture for the materials selection module

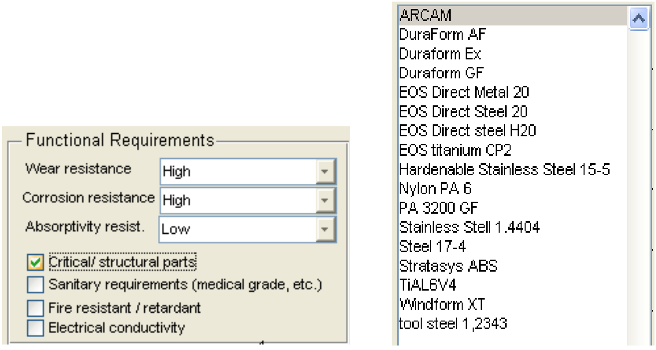
The first parameters to be selected are shown on Figure 9.30. These include: Wear resistance = High, Corrosion resistance= High, and Absorptivity = Low. The resulting list shown to the right is not restrictive enough as it still includes at least one material for each of the seven different RM processes included, thus the screening process must continue in order to find the materials that best fit the task.


Functional Requirements
Wear resistance: High
Corrosion resistance: High
Absorptivity resist.: Low
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

3D Systems AccuDur 100
3D Systems Accura SI 10
3D Systems Accura SI 40
ABS P400
ABSi P500
ARCAM
Accura Amethyst
Accura Bluestone
Accura SI 20
Accura SI 30
Accura SI 50
Accura Si 45HC
CastForm
Ciba (for SLA)
Du Pont (for SLA)
DuraForm AF
DuraForm Flex
Duraform Ex
Duraform GF
Duraform PA
EOS Direct Metal 20
EOS Direct Steel 20
EOS Direct steel H20
EOS titanium CP2
Hardenable Stainless Steel 15-5

Figure 9. 30 Initial materials screening list

As the final clutch pedal will be used under demanding conditions and its failure might lead to undesirable consequences, its function is considered as critical. Therefore by activating the ***'Critical/ structural parts'*** checkbox, the candidate materials are reduced to a more restricted selection (Figure 9.31).



Functional Requirements

Wear resistance: High

Corrosion resistance: High

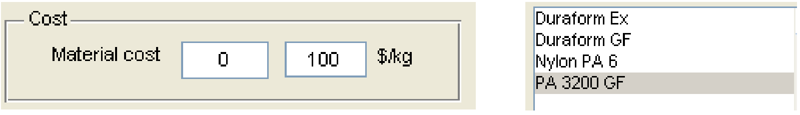
Absorptivity resist.: Low

☑ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

ARCAM
DuraForm AF
Duraform Ex
Duraform GF
EOS Direct Metal 20
EOS Direct Steel 20
EOS Direct steel H20
EOS titanium CP2
Hardenable Stainless Steel 15-5
Nylon PA 6
PA 3200 GF
Stainless Stell 1.4404
Steel 17-4
Stratasys ABS
TiAL6V4
Windform XT
tool steel 1,2343

Figure 9. 31 Restrictec screening list by aplying the "Critical condition"

The next steps are left to the designer's consideration. For instance if the materials cost is a more important factor compared to mechanical properties, the ***'Max-Min cost'*** window will be activated. The figure below shows a restricted material selection window in the case a maximum material cost of 100$ is established.



Cost

Material cost: 0 – 100 $/kg

Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF

Figure 9.32 Final restricted list by Price constraints

The charting area of the materials selection interface can display a series of material properties charts to aid during the materials selection stage. Following the product specifications the main mechanical properties to be observed are the *modulus of elasticity* or *tensile modulus* and *density*. This graph can be selected from the pop-up menu in the chart area; it illustrates the trade-off between material properties and cost (Figure 9.34).

The following example (Figure 9.33) shows two preliminary winners: the Duraform GF and Windform XT, both pertaining to the SLS process. The Duraform GF material is a glass-filled polyamide usually used for physical testing and functional use. It is usually applied to automotive parts intended to withstand high temperature rates. On the other hand, the Windform XT is a polyamide and carbon based composite material specially formulated for the SLS process, which seems to have superior properties, at least from the manufacturer specifications.

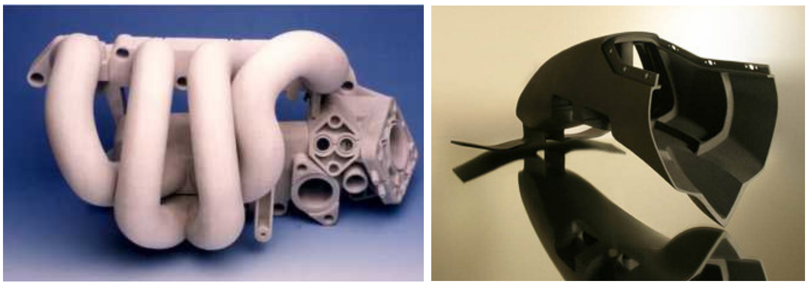
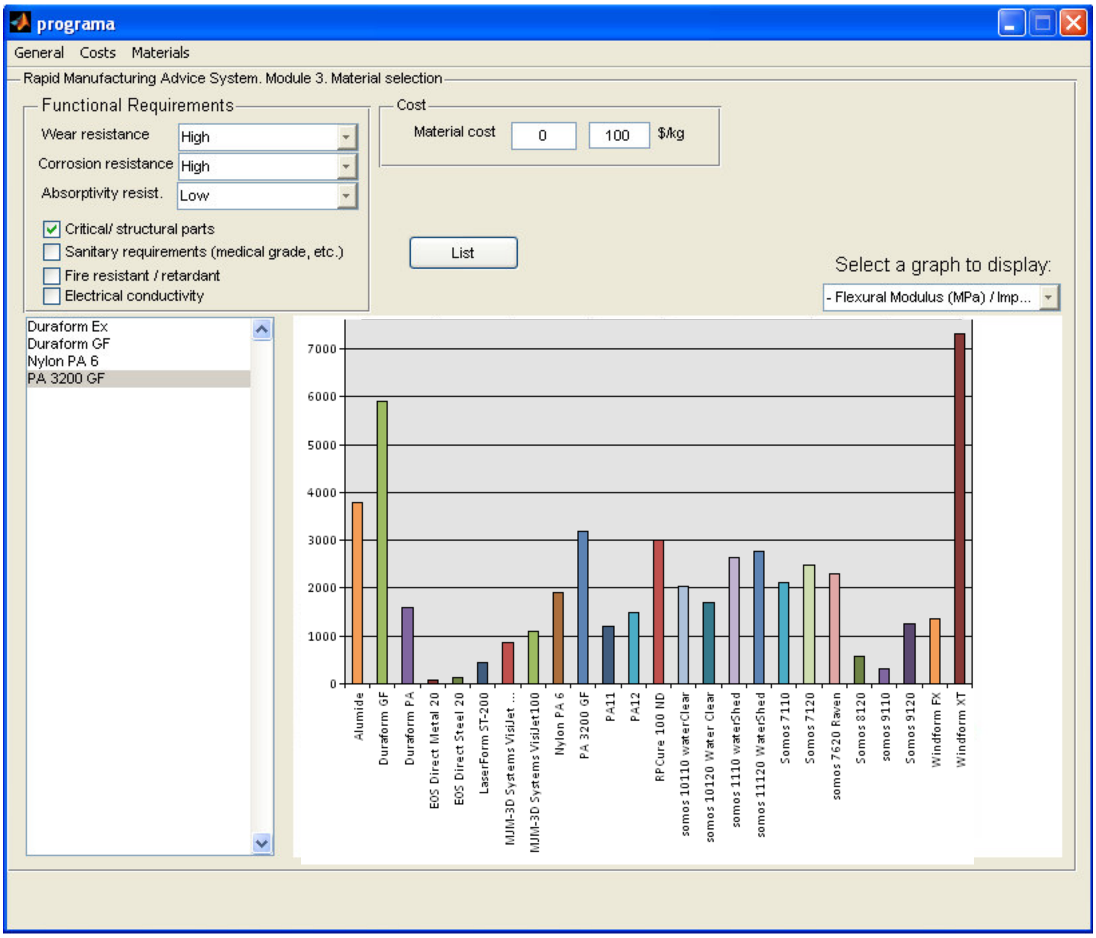


Figure 9.33 Two automotive parts built with the selected materials. Left) Manifold made with Duraform GF (3D systems, 2008), Right) Formula 1 front nose made with Windform XT (C.R.P Technology, 2009)



Wear resistance: High
Corrosion resistance: High
Absorptivity resist.: Low

☑ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

Material cost: 0 – 100 $/kg

Select a graph to display: - Flexural Modulus (MPa) / Imp...

Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF

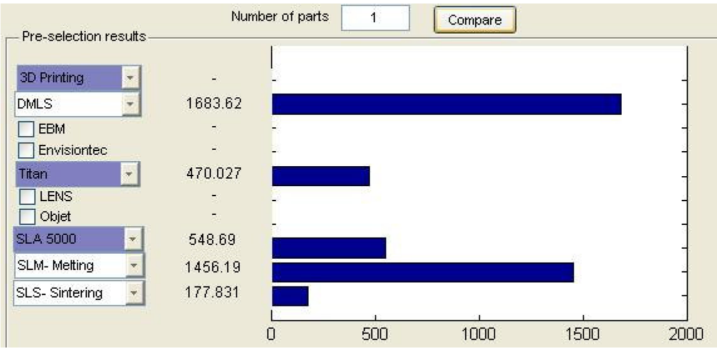
Figure 9.34 Materials selection results and graphical information of the Materials Selection Module

Altough this prelimiar materials selection has shown two material candidates, by no means will this selection represent the final feasible result; it should be rather considered as an potential alternative to the original injection molding of fiber reinforced composites that had been considered as the default process for making the clutch pedal.

It may be fair to doubt about the real capacity of Laser Sintered Powders to withstand the operating conditions of the clutch pedal; therefore one extra query to be solved is: which is the difference in cost between metallic and polymer based materials? Since for the designer it might be risky to trust on recently formulated polyamides, he may want to asses the feasibility of their metallic counterparts. This can be analyzed on the Cost Module.

9.3.3 STEP 3. Cost comparison

The following image (Figure 9.35) illustrates the cost estimation for a number of selected processes which will calculate the preliminary cost for a single part. It can be seen how metal based processes are by far more expensive than polymer based. A single comparison between DMLS and SLS shows a difference of 1000% between the metal and polyamide-made part.



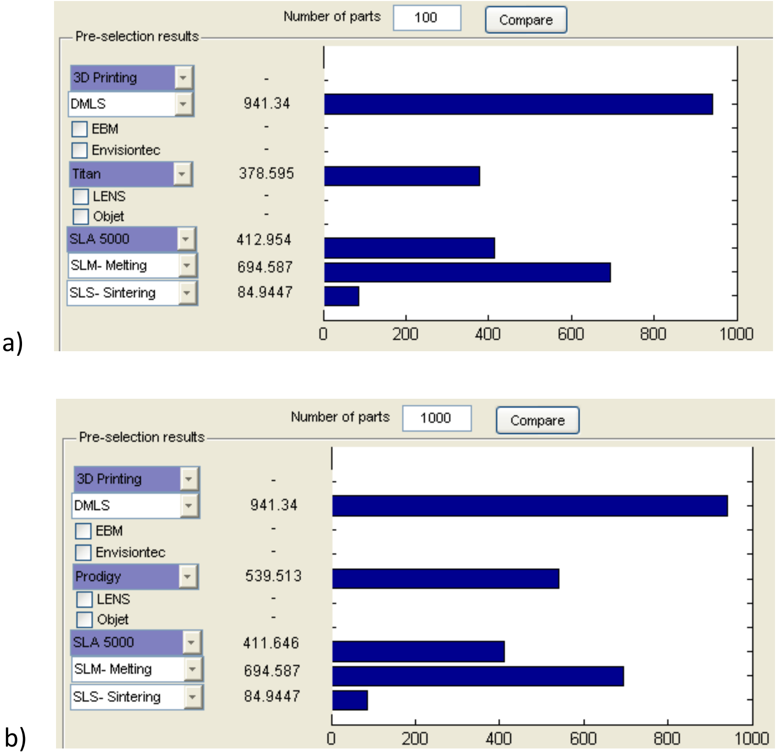
Number of parts 1

Pre-selection results

3D Printing	-
DMLS	1683.62
☐ EBM	-
☐ Envisiontec	-
Titan	470.027
☐ LENS	-
☐ Objet	-
SLA 5000	548.69
SLM- Melting	1456.19
SLS- Sintering	177.831

Figure 9. 35 Cost estimation for a single part

It is also possible to calculate the costs of low volume production as has been explained in the cost model chapter. In this way when a batch size of 100 parts is introduced in the costing module interface, the cost of metal based processes drops as shown on Figure 9.36. However if a batch size of 1000 parts is introduced there are no major changes in the parts cost.



a)

Number of parts 100

Pre-selection results

3D Printing	-
DMLS	941.34
☐ EBM	-
☐ Envisiontec	-
Titan	378.595
☐ LENS	-
☐ Objet	-
SLA 5000	412.954
SLM- Melting	694.587
SLS- Sintering	84.9447

b)

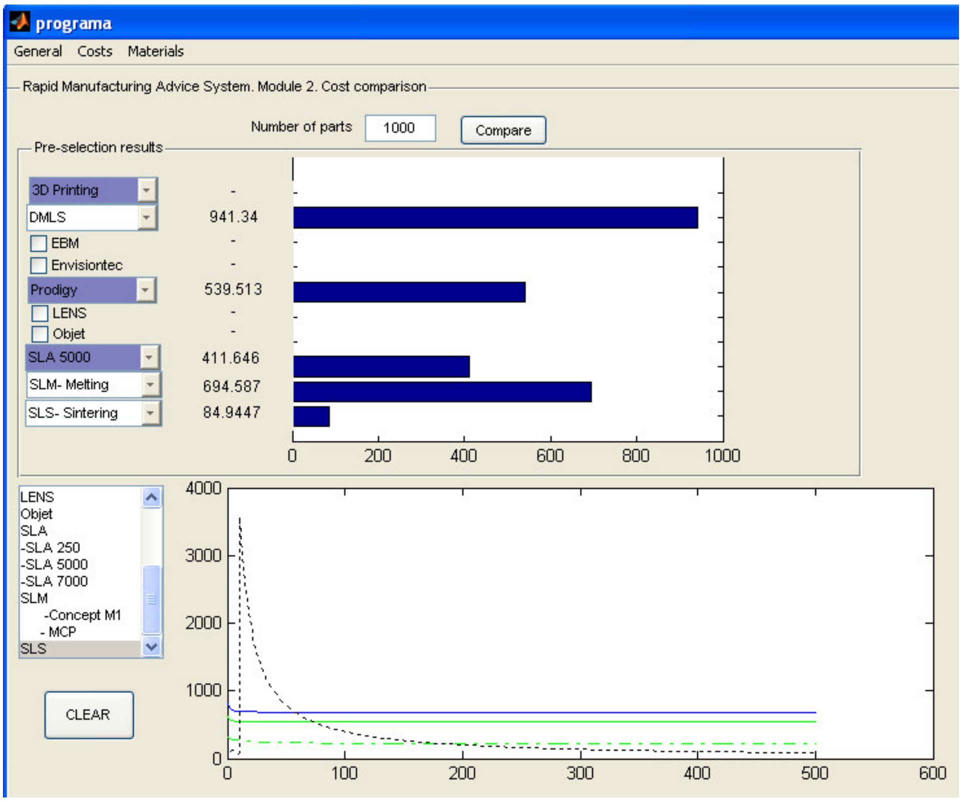
Number of parts 1000

Pre-selection results

3D Printing	-
DMLS	941.34
☐ EBM	-
☐ Envisiontec	-
Prodigy	539.513
☐ LENS	-
☐ Objet	-
SLA 5000	411.646
SLM- Melting	694.587
SLS- Sintering	84.9447

Figure 9. 36 Cost per part affeted by production volumes

The chart at the bottom of the user interface (Figure 9.37) shows an economic batch comparison between all the processes selected in the List box to the left. It is intended to simulate variable production volumes and the corresponding part cost. This figure shows the economic Batch comparison between the Laser Sintering process, and three different FDM machines (Prodigy, Titan and Maxum). As mentioned earlier in this work, the SLS cost estimation module has been designed by means of Artificial Neural Networks, based on a DTM Vanguard machine; therefore this estimation may not be extrapolated to other SLS equipment, as indivially designed ANN models would be necessary.



Number of parts: 1000

Figure 9. 37 Screen capture of the resulting Cost estimation graphs

By using the previously generated economic-batch graph for the selected RM processes, it is possible to compare an approximate cost against the conventional Injection Molding of composites that was originally considered. The comparison graph is shown below. It is possible to observe for this sample case that most RM technologies are not capable of providing an economic-batch bigger than a few dozen parts; however the SLS process has the biggest break-even point with nearly 400 units. From this point on wards it will be in the engineer's /designer's hands to take the next step, whether it is to modify some parameters and continue experimenting, or go further into the SLS process to prepare a set-up for real production and get actual quotes from service providers.

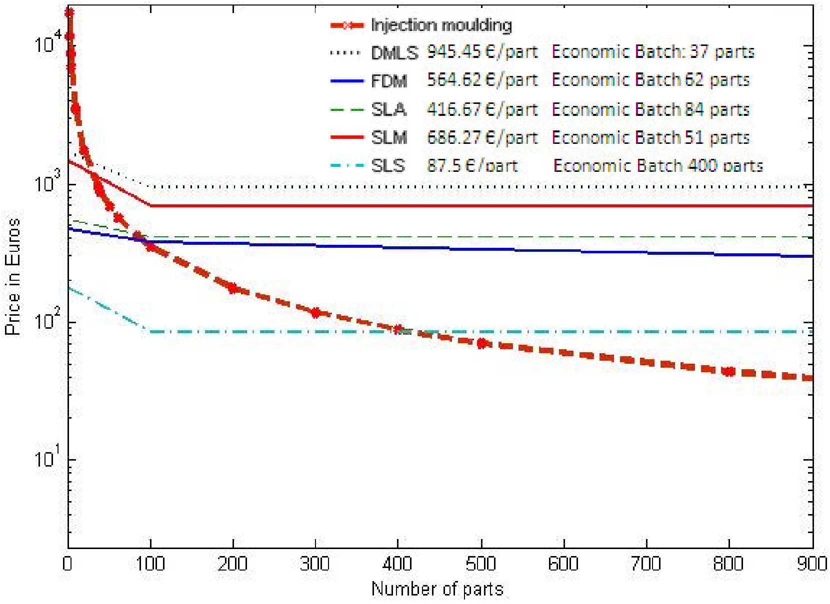


Figure 9. 38 Break-even curves of RM technologies vs. Ingection moulding

The analysis shown illustrates the Technical and economical possibilities for using Rapid Manufacturing as a possible production process. The results show a number of possible processes and their materials however the main drawback remains the cost per part. Metallic processes provide an elevated cost per part which is reflected in a moderate break-even against the original Injection Molding process; however for unitary parts they seem to be feasible options. On the other hand the SLS process presents a more convenient economic batch of nearly 400units however due to the nature and end use of the studied part, not many materials seem to be effective and it would be necessary to undertake further testing.

The results presented by the RMADS system however do not include the finishing and post-processing steps which usually increase the price per unit, however this preliminary assessment during conceptual design seems to be valuable to explore new alternatives before committing to a single process.

9.4 Case study 4. Coins Classifying Machine (CCM)

A special case study which is focused on modified material properties is presented herein. It consists on a Coin Classifier Machine (Riba Romeva, 2002; Llorens, 2007) which is comprised of different sub-systems: mechanical, electrical, magnetically and aesthetical. This case study is focused on internal mechanical parts responsible for the transportation and fixation of the coins to be classified. This sample case has been deliberately selected as the original design intent has been already designed with Polyamide based internal parts, however it also shows a number of limitations of RM regarding materials compositions which may comprise a subject l for further research.

The Coin-Classifying Machine is a project developed at the CDEI Centre, outsourced by a third party company; the objective was to develop a universal and modular coin-classifying device by means of an electromagnetic principle (Figure 9.39).

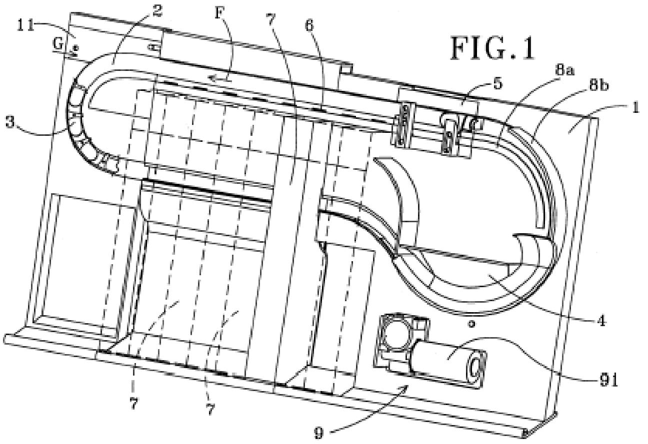


Figure 9.39 General scheme of the CCM machine. Source: Patent ES 2158803 B1, (UPC, 2001)

The overall system is internally composed of a plastic transporting band which contains individual “links”. These are independently designed parts with the function of guiding individual coins along the path of the transport band. For this purpose the links incorporate a number of geometrical features to be highlighted. These are described in Figure 9.40.

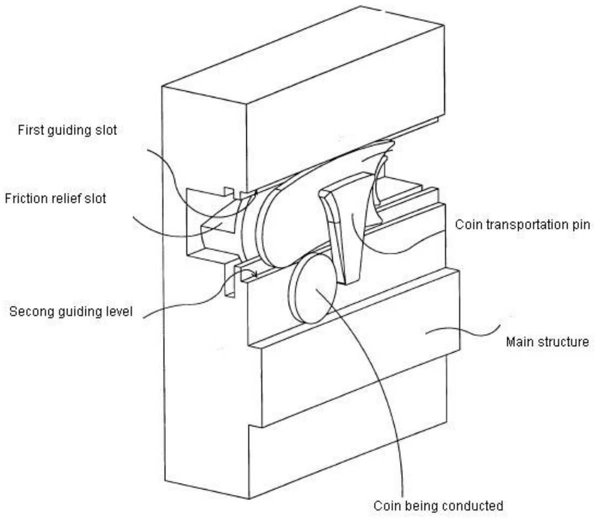


Figure 9. 40 Internal elements and their interactions. Source: Patent ES 2158803 B1, (UPC, 2001)

This system guides the introduced coins through a recognition system which evaluates the authenticity of the coins by inspecting geometrical features such as: thickness, diameter, roundness and material parameters based on electro-magnetic methods based on metals and alloys characteristic responses to impulses. This electromagnetically principle is the main constraint imposed to the analyzed system, since only polymer based links and transporting bands can be utilized. One of the most challenging elements are the so called *'links'*, or *'connectors'* as shown on Figure 9.41, as the materials to be applied must fulfill the following conditions:

- High Dimensional precision
- Lightweight
- Slippery material
- High impact resistance
- High repeatability
- Non conducting material
- High general mechanical properties
- High corrosion resistance

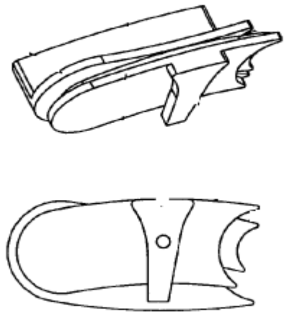


Figure 9. 41 Perspectives of the "link" polymer part (UPC, 2001)

The initial materials consideration for these elements has taken into account the following materials shown in Table 9.4, according to their behavior, mechanical and functional properties.

Table 9. 4 Originally considered materials for the plastic conectors

PA 6, PA 66, PA11, PA12. Polyamides, (Nylon)	Semi-crystalline thermoplastic typically used in Gears; cams; rollers; bearings; nuts and bolts; power tool housing; electrical connectors; combs; Coil formers; fuel tanks for cars especially in its molded form. However the mechanical properties of this polymer are dramatically reduced with water absorption therefore the final part must be sealed in case there will be a contact with humidity sources.
POM: Polyoxymethylene.	It is usually used in sprockets; springs; gears; cams; bushings; clips; lugs; door handles;

	window cranks; housings; seat-belt components and other accessories. This material is degraded by contact with zinc ions.
PE-UHMW. Polyethylene, Ultra High density.	Utilized in pipes; toys; bowls; buckets; milk bottles; crates; tanks; containers; film for packaging; blown bottles for food.
PTFE: Polytetrafluoro-ethylene:	Specially used in high temperature electrical insulation; coating for non-stick applications, impellors; pipes; gaskets and other elements.
PI: Polyimide:	Used for bearings, electrical insulation; engine parts; printed
PET: Polyethylene Terephthalate.	circuit boards, film (Kapton) for capacitors; coatings for electrical components. Some uses: Electrical fittings and connectors; blow molded bottles; packaging film; film.
PEEK: Polyether-etherketon:	Main uses: Wire covering; injection molded engineering products; film for flexible PCB; resin in fiber prepegs; aerospace applications; radiation environments

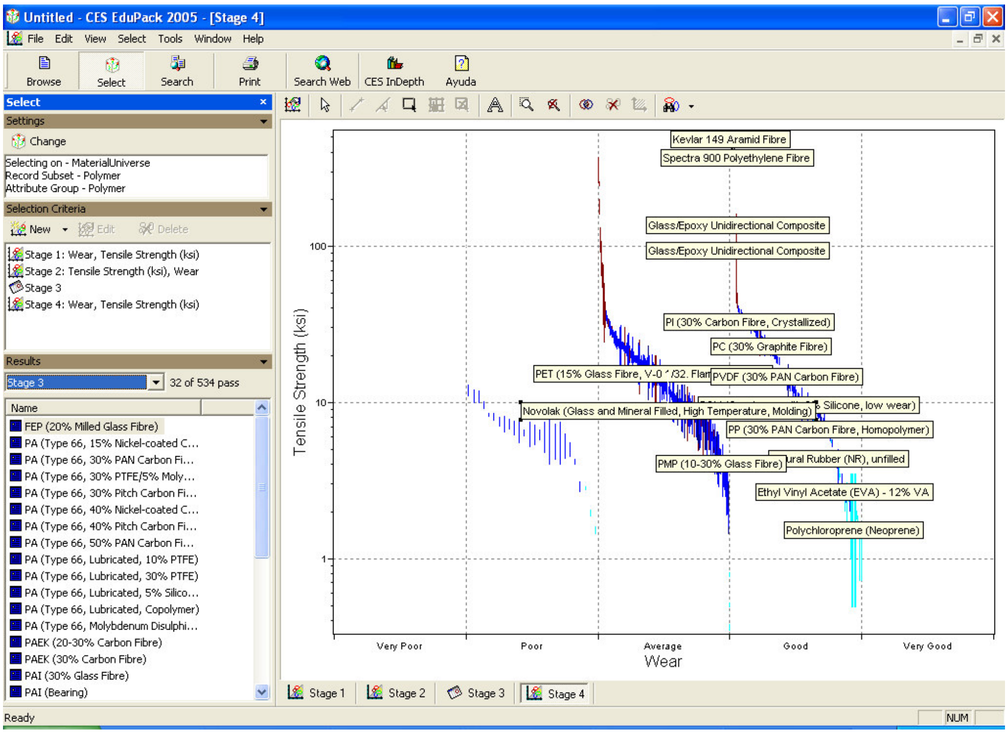
One interesting remark is the criteria used for the analysis of this element, based on three basic issues:

1 – Material properties: wear, friction, tensile strength, impact resistance

2 – Manufacturing process: Feasible process based on shape and material

3 - Costing factors

By running an advanced search on Cambridge Materials selector (Granta, 2007) it is possible to compare different mechanical , thermal and general performance parameters in order to restrict the number of choices. When the corresponding properties for Wear resistance, Tensile strength, Abrasion and corrosion resistance are set it "High" it is possible to see how most of the surviving options are Polyamides and fiber-glass reinforced materials (Figure 9.42).



Selecting on - MaterialUniverse
Record Subset - Polymer
Attribute Group - Polymer

Stage 1: Wear, Tensile Strength (ksi)
Stage 2: Tensile Strength (ksi), Wear
Stage 3
Stage 4: Wear, Tensile Strength (ksi)

Stage 3 — 32 of 534 pass

FEP (20% Milled Glass Fibre)
PA (Type 66, 15% Nickel-coated C…
PA (Type 66, 30% PAN Carbon Fi…
PA (Type 66, 30% PTFE/5% Moly…
PA (Type 66, 30% Pitch Carbon Fi…
PA (Type 66, 40% Nickel-coated C…
PA (Type 66, 40% Pitch Carbon Fi…
PA (Type 66, 50% PAN Carbon Fi…
PA (Type 66, Lubricated, 10% PTFE)
PA (Type 66, Lubricated, 30% PTFE)
PA (Type 66, Lubricated, 5% Silico…
PA (Type 66, Lubricated, Copolymer)
PA (Type 66, Molybdenum Disulphi…
PAEK (20-30% Carbon Fibre)
PAEK (30% Carbon Fibre)
PAI (30% Glass Fibre)
PAI (Bearing)

Figure 9.42 Screen capture of the Material-Universe in the CES Edupack software.

Selection of polymer materials

All previous materials share different properties which make them fine candidates. For instance while PPS has elevated mechanical performance and a wide range of working temperatures, other options such as PET and PBT possess better frictional behavior and dimensional stability. PEEK has also adequate thermal and mechanical properties however it high costs puts it off-the list of candidates. On the other hand all Polyamide materials exhibit good-enough mechanical properties at a low cost, however their main limitation is their high water absorption which may affect their performance under continuous operation.

As the final deciding factor is cost, the final material selection was PA-66 as final material for the guiding system coupled with POM for the moving Links. For the final part several tests had to be performed by injection molding in order to get the adequate performance. These experiments included different material modifications such as: glass fiber reinforcement, lubricant addition and additives addition (such as steel and carbon micro-fibers for enhanced wear resistance improvement).

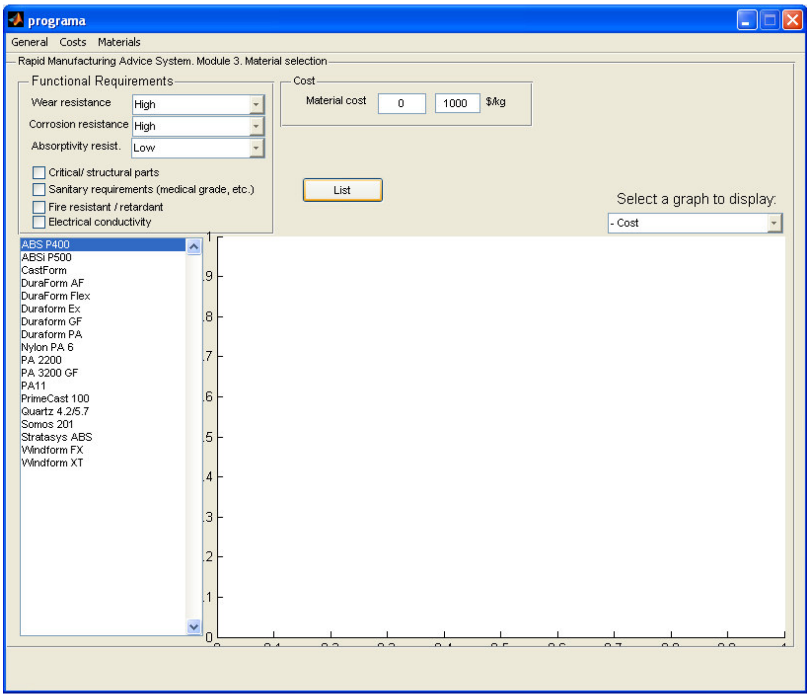
The final manufacturing process selected was Injection moulding. In order to mould correctly the designed part it was necessary to design a complex ejection system due to the multiple cavities added to the plastic part(Figure 9.43). The selection of the Injection molding process indicates that low volume production of the CCM machine would be influenced by high tooling costs, therefore it is interesting to explore alternative means of fabrication.

Figure 9. 43 Image of the moving “links” with wear marks due to continuos movement inside the machine and contact with coins

9.4.1 Step 1. Materials selection Module

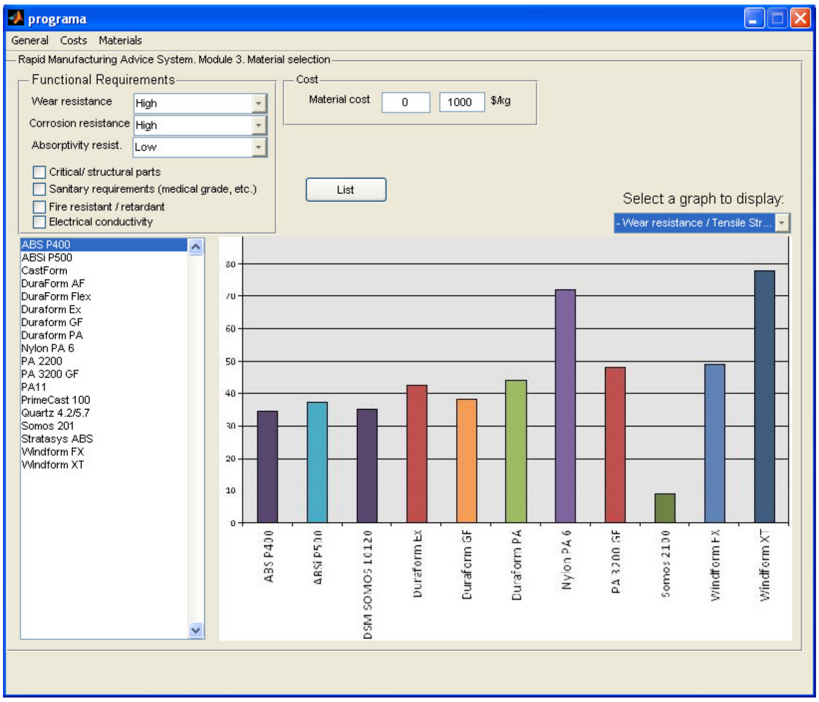
As described previously the first screening criteria is related to material properties, thus the materials selection module will be activated before the other modules in the RMADS system. In the main window (Figure 9.44) the following parameters are activated, following the original part’s PDS:

- Wear resistance = High
- Corrosion resistance = High
- Absorptivity = Low
- Material type = Polymer



Wear resistance: High
Corrosion resistance: High
Absorptivity resist.: Low
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity
Material cost: 0 – 1000 $/kg
Select a graph to display: - Cost

Figure 9. 44 Screen capture of the initial Material selection results



Wear resistance: High
Corrosion resistance: High
Absorptivity resist.: Low
☐ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity
Material cost: 0 – 1000 $/kg
Select a graph to display: - Wear resistance / Tensile Str...

Figure 9. 45 Materials selection module and the comparison grapgh being displayed

The preliminary selection screen shown above still includes a rough list of materials without applying more restrictive factors. For instance the materials Castform and PrimeCast which are intended for casting process are not really suitable candidates. However while an experienced designer may know this, it will not be evident for new comers or non experienced designers, therefore further analysis must be undertaken.

As the wear resistance and overall mechanical properties are important for the final design, the Listbox at the upper right hand is activated by selecting the Wear resistance/ Tensile strength graph as shown on Figure 9.45.

The listbox displays the best relationship between both properties for the selected materials in the previous screening. From there, is possible to observe how "in theory" the best relationship corresponds to the

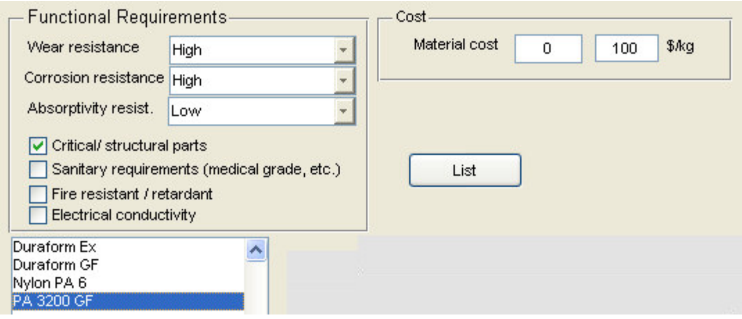
Windform series of materials followed by non-reinforced PA polymers. This however may open the debate on material properties: How does the SLS process behaves with custom-made, fiber reinforced, carbon-filled tailored powders? It may be only responded through experimentation. The following chart shows the theoretical values for the Tensile Strenght (MPa) for the originally proposed materials and the RM materials resulting on the Figure above, it is evident that engineered thermoplastics still yield significant advantage versus laser sintering powders however the designer has the last word over the minimum-enough Tensiles Strenght to perform the task.

Table 9. 5 Tensile Strenght values for Powder based and engineering thermoplastics

RM material	Tensile strength (MPa)	IM material	Tensile strength (MPa)
Windform XT	77	PA 66 (Filled)	117
PA 66	72	POM (25% glass filled)	110
Windform FX	48.9	PA 66 unfilled	62
PA 3200 GF	48	PE (20-30% glass filled)	55
Duraform PA	44	POM (30% carbon fibre)	51.54

While mechanical properties seem to be superior for Windform XT, there is no available data regarding absorptivity levels. The same is true for some of the other materials selected therefore it must be clarified again that the results provided by the system will be on the basis on theoretical information available from materials manufacturers and by no means will replace functional testing and user experience.

Being the reinforced Polyamides for Selective Laser Sintering the best theoretical option, it is interesting to apply additional factors to the screening process. Since cost is considered as a restricting factor, a maximum cost of 100 €/kg is applied, hence reducing the list to four alternatives. Also the parameter “critical” is activated since the mechanical response of the studied element would not result in catastrophic failure but would influence in the mal-functioning of the overall system (Figure 9.46).


Functional Requirements
Wear resistance: High
Corrosion resistance: High
Absorptivity resist.: Low
☑ Critical/ structural parts
☐ Sanitary requirements (medical grade, etc.)
☐ Fire resistant / retardant
☐ Electrical conductivity

Cost
Material cost: 0 – 100 $/kg

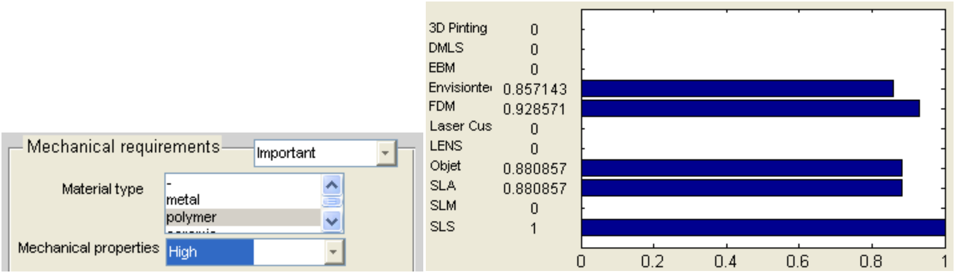
Duraform Ex
Duraform GF
Nylon PA 6
PA 3200 GF

Figure 9.46 Final materials list with the material cost restrictions applied

The figure above restricts the overall selection task to only one process: Selective Laser Sintering. The second task however is to assess the physical feasibility of the process to evaluate its performance over the geometrical features required.

9.4.2 Step2. General requirements Module

As defined in the previous step the material preference is set to polymer-type and mechanical properties needed are High (Figure 9.47), also the importance factor in the upper right corner is set to ***‘Important’***, showing the results of the figure below.



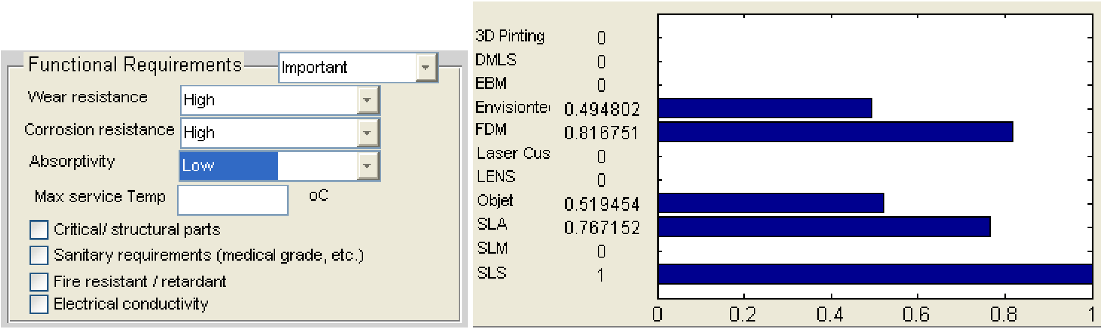
Mechanical requirements: Important

Material type: - / metal / polymer

Mechanical properties: High

Figure 9.47 Initial ranking affected by Mechanical requirements

The box selected on the second place is related to functional requirements, as shown on the previous Step these are related to material properties. Figure 9.48 shows the resulting graph which already exhibits a major suitability of the SLS process.



Functional Requirements: Important

Wear resistance: High

Corrosion resistance: High

Absorptivity: Low

Max service Temp: oC

☐ Critical/ structural parts

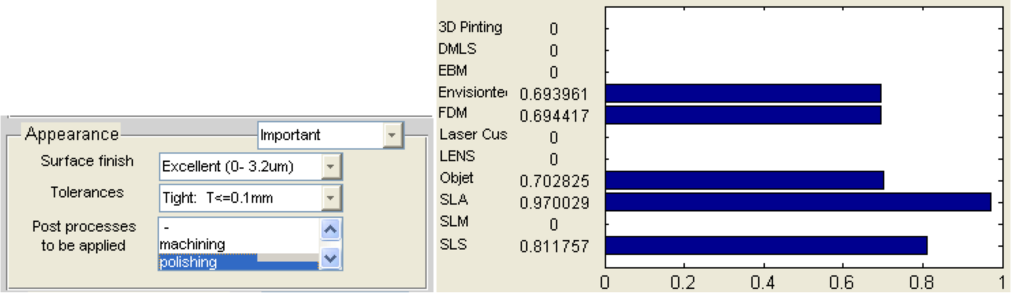
☐ Sanitary requirements (medical grade, etc.)

☐ Fire resistant / retardant

☐ Electrical conductivity

Figure 9.48 Process Ranking affected by Functional requirements parameters

The next step is related to Appearance. Although the '*Links*' are internal parts, their movement inside the machine makes it necessary to have ***'Excellent'*** surface finish near to that of molded parts. Additionaly, ***'Tight'*** tolerances are required in order to interact effectively with the electro-magnetic system of the CCM equipment. Interestingly, when the importance attribute is set to ***'Important'*** for the '***Appearance'*** box, the SLA process improves its ranking as it can provide superior finishing and tolerances (Figure 9.49).



Appearance: Important

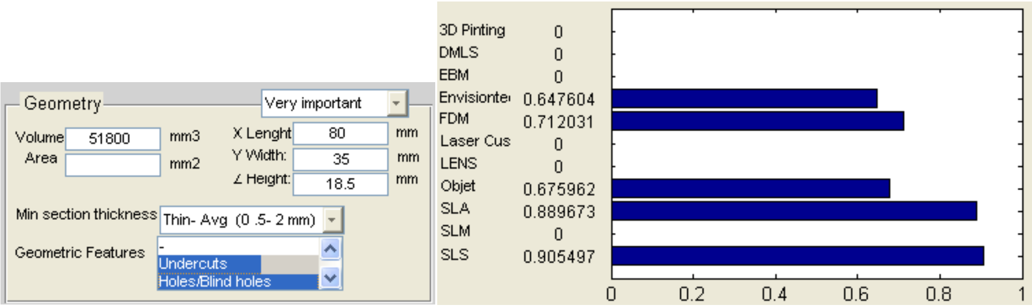
Surface finish: Excellent (0- 3.2um)

Tolerances: Tight: T<=0.1mm

Post processes to be applied: - / machining / polishing

Figure 9.49 Process ranking affected by Appearance parameters

Finally the geometric requirements are entered along with the part dimensions. For this case a ***'Thin to average'*** section thickness is required for the final part and also it is necessary to specify a number of features such as: ***'undercuts'*** and ***'blind holes'*** contained in the geometry. The resulting final graph (Figure 9.50) shows how the SLS and SLA processes fulfill the conditions equally. It is worthwhile to know that the ***'Critical part'*** checkbox has not been activated in order to observe the qualification of the other processes; otherwise SLS would be the only alternative.



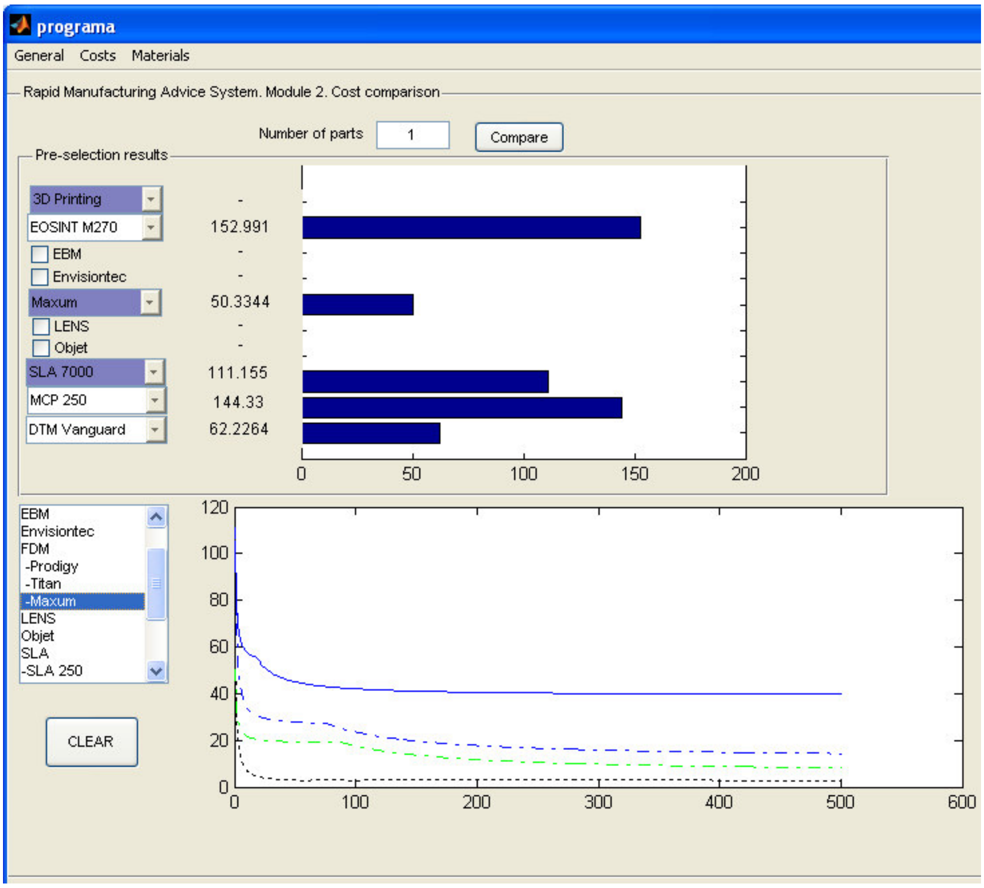
Geometry: Very important
Volume 51800 mm3
Area mm2
X Lenght 80 mm
Y Width: 35 mm
Z Height: 18.5 mm
Min section thickness: Thin- Avg (0.5- 2 mm)
Geometric Features: - Undercuts Holes/Blind holes

3D Pinting 0
DMLS 0
EBM 0
Envisiontec 0.647604
FDM 0.712031
Laser Cus 0
LENS 0
Objet 0.675962
SLA 0.889673
SLM 0
SLS 0.905497

Figure 9. 50 Final ranking affected by Geometric restrictions

9.4.3 Step 3. Costing module

Once proved the theoretical feasibility for building the studied part with the SLS process, it is possible to foresee the economic alternative of this technology versus other RM methods, specifically the Injection molding process. Consider an injection mould cost of 25,000€. This is a conservative cost since the intended mould would include movable ejector pins and a highly resistant base material to withstand the abrasion of fiber reinforced thermoplastics. When activated, the RMADS costing module presents the appearance shown on Figure 9.51.



Rapid Manufacturing Advice System. Module 2. Cost comparison

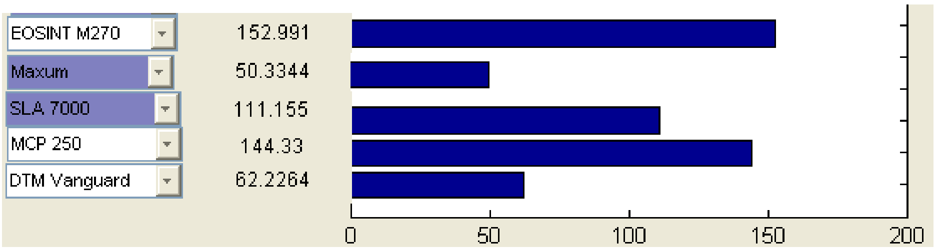
Number of parts 1

Pre-selection results

3D Printing -
EOSINT M270 152.991
☐ EBM -
☐ Envisiontec -
Maxum 50.3344
☐ LENS -
☐ Objet -
SLA 7000 111.155
MCP 250 144.33
DTM Vanguard 62.2264

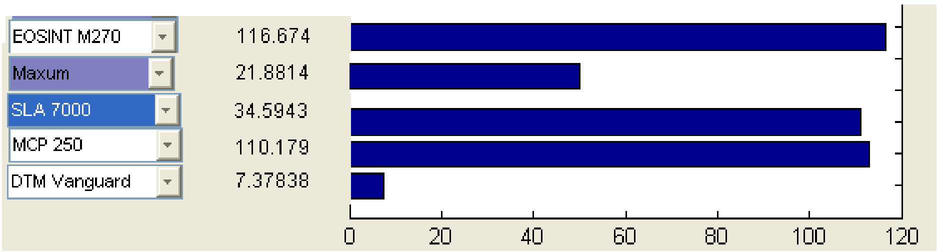
Figure 9.51 Screencapture of the Costing Module with the estimation for a single part

The following sequence shows the evolution of cost for the different machines selected, namely: a EOINT M27o for DMLS, a Maxum machine for FDM, a SLA 7000 which is the biggest sized machine on the database for SLA a MCP 250 for SLM and a DTM vanguard for SLS.



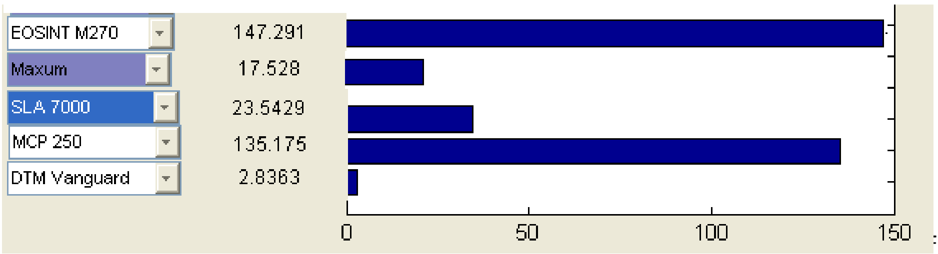
EOSINT M270 152.991
Maxum 50.3344
SLA 7000 111.155
MCP 250 144.33
DTM Vanguard 62.2264

Cost per part for a single unit



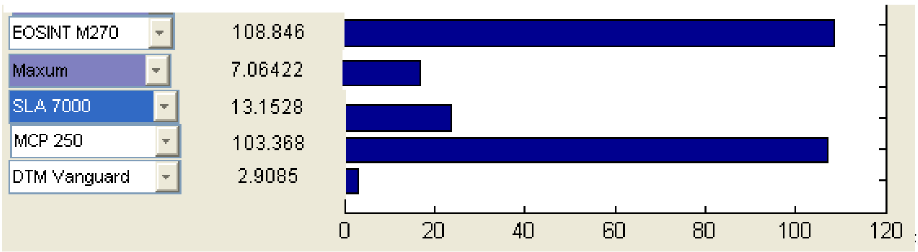
EOSINT M270 116.674
Maxum 21.8814
SLA 7000 34.5943
MCP 250 110.179
DTM Vanguard 7.37838

For 10 parts



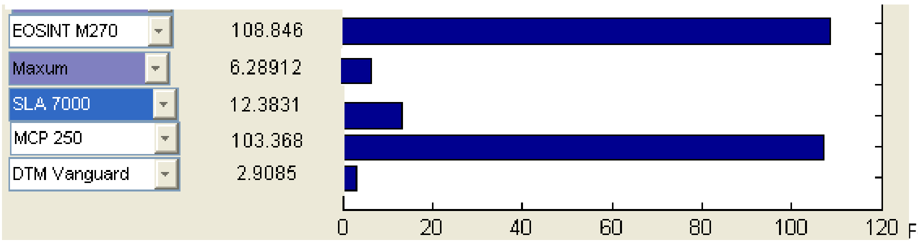
EOSINT M270 147.291
Maxum 17.528
SLA 7000 23.5429
MCP 250 135.175
DTM Vanguard 2.8363

For 100 parts



EOSINT M270 108.846
Maxum 7.06422
SLA 7000 13.1528
MCP 250 103.368
DTM Vanguard 2.9085

For 1000 parts



EOSINT M270 108.846
Maxum 6.28912
SLA 7000 12.3831
MCP 250 103.368
DTM Vanguard 2.9085

For 3000 parts

Figure 9. 52 Evolution of cost estimation for different production volumes

The previous graphs show the benefits of using the SLS process versus other RM technologies, however it is interesting to observe the evolution of part cost for more RM alternatives.

The following graphs (Figure 9.53) show the cost comparison graph between the Injection molding process and its SLS counterpart, where the approximate break-even point is located around 20,000 parts, that is from low to mid-volume batches.

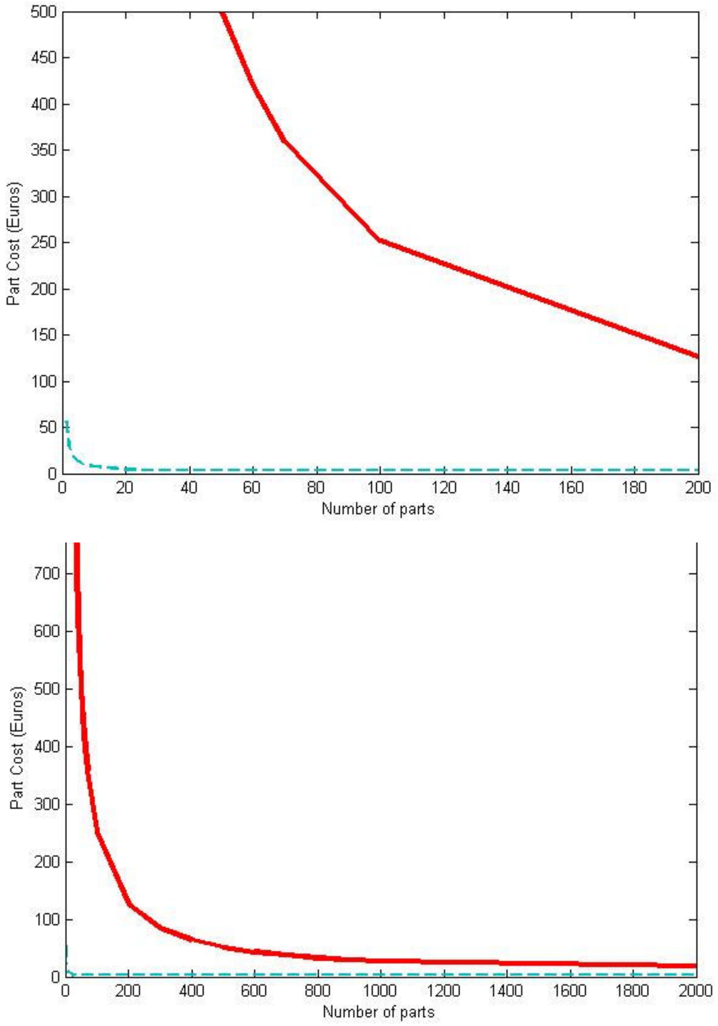


Figure 9. 53 Break even curves for the SLS process (dotted line) vs. Injection Moulding (continuous line)

With this conclusion it can be established that from the competing processes SLS is technically feasible, cost effective and provides similar material properties to those provided by the injected polymers. The next step could include a prototype test under functional conditions during repetitive-prolonged cycles in order to validate the viability of this solution.

9.5 Conclusion

This Final chapter has included four different Case studies where the opportunity of applying Rapid Manufacturing may guide to opportunities for cost reduction, design optimization or optimal production batches. There is a lack of applied cases in literature where the pros and cons of using RM are evaluated, apart from manufacturers and service providers “White papers” where the capabilities of additive manufacturing are generally proved with attractive and complex designs. Indeed, the ultimate goal of RM is not the fabrication of complicated yet fashionable items for one-off production, but to increasingly find new niche markets where its capabilities are contrasted versus conventional processes.

In the cases shown in this Chapter the metal casting process and injection molding have been analyzed in the search for an additive alternative when they turn inefficient in terms of costs and quantity.

Also an exploration has been performed on the materials available for RM and their potential to meet functional requirements of end-use parts. As a result there are a number of results that suggest exploring the potential of RM while in other cases it is not recommended:

1- In the first case, the connecting rod fabricated by metal casting cannot be replaced by any RM technology for volumes higher than 220 units. This part performs a critical function within the system therefore a metal RM process would be preferred but their break-even points shown no benefit for more than 10 parts. Regarding material properties and manufacturability the design of the connecting rod show no further restrictions and might be even optimized.

2- The second case, the moving block shows a typical case where no RM method has proved to be an economically feasible alternative to the casting process. The main obstacle is the part size which occupies an important fraction of the building vat and also needs support structures in every possible orientation. This is a drawback especially for metallic processes where the use of such structures means higher post processing time for material removal, hence increasing the estimated cost.
On the other hand, an alternative mechanism has been introduced (Munguía et.al., 2007) which is based on a different moving principle to transmit movement, resulting in a lighter and smaller part with a better cost relationship (a break-even point around 450 units per year for the SLS project and 10 units for metal-based)

3- The clutch pedal is a challenging part originally intended for carbon-fiber injected polymers. Through this analysis a number of carbon reinforced polyamides have been compared and economic prediction volumes calculated for all RM processes. Interestingly, metal based RM methods provide higher break-even points than previous examples with economic quantities ranging from 37 to 51 parts when compared to the Injection molding process. Again SLS has shown the highest economic batch with around 400parts

4- The case study of the “link”, a small-movable part that forms a chain inside a coin classifying machine, is the most restricting sample case. The initial specifications provided by the designer show a previous range of suitable polymeric materials with special emphasis on wear resistance, absorptivity and mechanical properties. It made it necessary to run the material selection module before the others in order to assess the capability of RM materials. This showed the efficiency of the RMADS system to perform screening stages of materials, however it must be noted that the database used is still limited and there may be newer material options with enhanced properties not considered for this sample case.
Regarding economical feasibility, the SLS process showed its major advantages due to the shape and size of the part, indicating an approximate break-even point of 25,000 units vs. injection molding. This is a significative quantity for low-mid volume manufacture.

As additional remark it can be noted that none of the designers and manufacturers studied in this chapter had considered previously the option of RM as alternative production method. Also, the re-design opportunities that arise from applying RM have not been explored. It is expected that with further redesign the studied parts and mechanisms will be prone to more optimum economic evaluations.

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10. Summary and conclusion

10. Summary and Conclusion

10.1 Summary

In this research a Knowledge Based Engineering system, RMADS, has been developed and implemented. Although it is not the first work on the topic of process selection for Rapid Prototyping it can be considered a precursor in incorporating more intelligence in the form of added modules which allow the concurrent selection of processes based on a designer's criteria with more informed background, instead of providing a simple ranking of winning processes.

It also can be considered the first selection model intended for Rapid Manufacturing, i.e. the aim is the evaluation for the final function instead of a punctual prototyping situation.

Although the overall project planning and budget did not allow undertaking physical experimentation (it can also be considered an issue for a separate Thesis!) the illustrated application cases have shown the functionality of the system under engineering design situations.

The RMADS system is a KBE model for selecting Rapid Manufacturing processes and materials. It is comprised by a number of artificial intelligence elements described along this work: an expert system for inference making through quantitative data, relational databases which are present across the different modules for making data retrieval and assessment of the best user selected options. The system also incorporates a Fuzzy-logic inference system for handling imprecise data especially regarding qualitative manufacturing parameters. Also Artificial Neural Networks are integrated within the system, along with parametric models in order to perform estimation tasks, relying on the info generated by previous modules.

The aim of this system is to aid in the selection of RM materials and processes during the first design stages however its use may be conditioned by different factors:

- The expertise and previous utilization of KBE by potential users: There is an issue regarding the real effectiveness of Computer Aided systems during conceptual design especially for mechanical engineering. It is assumed that for a experienced user with major expertise in the field of RM, some of the information provided by the RMADS system would not be necessary. On the other hand, for new-comers, young engineering design students and trainees, the system will provide valuable practical information that may only be obtained by means of consultancy with experts or higher specialization.
- The real level of trust in Rapid Manufacturing: For a vast number of potential users RM still remains unknown; also there is a misconception related with the earlier denomination of "Rapid Prototyping" as a technology for only getting prototype parts with rather low properties and fragile appearance. The last four years however, since the beginning of this research, there has been a massive introduction of new materials options which not only tend to "mimic real materials properties", but already incorporate special formulations for specific uses such as fibber reinforced PA powders
- The obsolescence and continuous updating of the system: Since the beginning of Rapid Manufacturing there have been numerous technologies appearing as technology breakthroughs but with little market impact. Many of these technologies still exist in Universities departments for research or technical improvements, however in order to provide a useful aid for design the proposed RMADS system can only compare those technologies with extensive commercial use and available technical specifications, including running and materials costs. It is important then to perform continuous system updates in order to be synchronized with the latest technologies advancements. The database structure is designed so as to facilitate this task however it requires the user intervention for introducing new data.

The system was designed in order to provide concurrent criteria for the selection of processes and materials in an iterative process where the final decision if left to the designer's criteria. As shown in the last case studies, according to the nature of the problem to be solved it is possible to start first with material selection which consequently narrows the availability of RM processes; on the other hand if the screening phase starts without a previous materials preference, the general requirements module provides a wider picture of the candidate processes and their relative effectiveness. This is the only "quantitative" module within the RMADS system as it provides a final bar graph with ranking in the interval [0-1].

The main emphasis of the general requirements module is on manufacturability issues of the intended parts. The part information that must be introduced can be obtained from standard .STL viewer; also the part features (holes, undercuts, overhangs, etc.) are manually selected. Appearance factors (surface finish and tolerances) are handled by means of fuzzy logic so that the user can select a predefined value described by linguistic terms, instead of entering an exact measure which usually is unknown by the user. The three-level list that is displayed in each case corresponds to the RM capabilities mapped on conventional manufacturing standards. That means for instance, that if very tight tolerances are needed, only those RM processes capable of providing such value will be given a higher grade. This criterion is one of the main differences when compared to previous selectors.

The same is true for functional requirements that are requested on this same module. However there is information still difficult to gather for RM processes such as wear resistance, corrosion and absorbtivity. As for a conventional material this information is given in qualitative forms such as "good, average, bad", the same criteria has been applied to RM however few RM to date include such specifications.

Regarding critical/structural part capabilities and sanitary requirements (medical grade, food compatibility, etc.) there is some controversy as some RM materials claim to have those properties however none of them has reported case studies of such application. This criteria is however included in the system, expecting further advances in the following years.

A rule-based system has been deployed in order to handle numeric and linguistic responses which are then translated to normalized vectors, directly influenced by the importance factor selected by the user. This feature provides the system with the sensibility for instance, to recognize when shape and appearance are more important than mechanical properties and vice versa.

The second module of Cost comparison performs separate calculations based on two costing models: parametric and neural network based. Their advantages and drawbacks have been already discussed however it is important considering that for this system they are complementary. Parametric models provide a general frame to perform estimations for a wider variety of processes with the handicap of a higher error rate in the estimation. On the other hand ANN-based models seem more accurate but their modelling requires a detailed implementation and analysis of the process to be modelled. As Cavalieri et. Al. highlighted in their previous work (Cavalieri, Maccarrone et al. 2004) there is a critical issue regarding ANNs, represented by the poor capabilities to interpret output data. Therefore it was preferred to adapt both approaches, parametric and ANN-based, in order to provide estimates sensible to variable production volumes. While most estimators predict the cost of multiple parts by extrapolating the cost of a single unit, the model integrated within the RMADS system is capable of considering indirect costs: machine costs, labour costs, machine and administrative overheads, and adjust the estimation proportionally to the production volume.

The last module of materials selection is inspired on the CES edupack system providing basic selection criteria for RM materials. The interface is compatible with Ms Access databases so that new materials can be added and consulted by means of ODBC calls. While this is a standards mode of operation for relational databases, the main contribution is the integration of such process into the global selection system.

A Matlab application has been implemented for this research, not as the final product but as a means for representing the models and selection criteria proposed along this research. Since there were several techniques to be applied, this software allows an easy integration of these different tools namely: relational databases, expert-system programming, rule-making, fuzzy logic toolbox, artificial neural networks, curve fitting and charting. However it has the disadvantage of making the system capable of running in different equipment of through internet-based services. This may be a new task requiring further work more likely for the programming and computer science domain.

10.2 Research contributions

Some of the major contributions from this research can be summarized as follows:

1. The work presented herein lays an innovative foundation for an integrated process-selection system which relays in the use of expert systems and artificial intelligence tools to aid the designer make an informed decision based on preliminary product data.
2. This research introduces one of the first methods to assess the suitability or not of Rapid Manufacturing as feasible production technologies. Differently from previous systems, the aim is the application of end-use parts instead of prototype models
3. The system provides a cost-estimation model capable of generating precise estimations from basic product data. Unlike commercial systems this cost is not based on Online-service bureaus calculations, but on costing factors, similarly to conventional production costing modules
4. The use of Artificial Neural Networks has been implemented for the first time on Rapid Manufacturing methods to perform cost estimations. This contribution has also been published in the form of paper due to its relevance (see publications annex)
5. The method and foundations presented in this Thesis can be extrapolated to other conventional technologies beyond RM. It introduces a general criteria and processing logic that can be well suited to similar selection tasks in other areas. This has also been suggested by comments from referees of some publications generated from this work.
6. This research developed and implemented a comprehensive KBE system capable of:

a. Integrating selection analysis tools
b. Reducing decision making process time and computation time for candidate Process selection

10.3 Recommendations for Further Research

Further research can be deployed in different fields of expertise. As this work can be considered as a confluence of manufacturing, design and KBE systems design knowledge there are a number of research lines identified which could be explored by futures researchers interested on this topic.

10.3.1 Design for Rapid Manufacturing Module.

When the thesis proposal was presented a DFRM module was included within the system. Soon it arose as a more complex area which requires a close analysis of design capabilities and optimization opportunities. This area has been investigated by several research groups and project consortiums within Europe. Furthermore this area deals with proprietary knowledge and expertise of manufacturers and service providers; therefore although there is much investigated, just a minor fraction has been disclosed to the public. DFRM for metals is especially interesting since metal parts are more likely to be used as final products than polymer powder –based parts. The Rapid Manufacturing Research Group at Loughborough University is an active group on this area; however it has the potential for being expanded to different groups.

10.3.2 Experimentation on functional properties

There is an important number of literature devoted to the analysis of benchmark parts produced trough Rapid Manufacturing means, however not all these work is useful as it provides isolated results for a special geometry and one specific process configuration. Also much of the research made is focused on measuring conventional mechanical properties (tensile strength, tensile modulus, etc.). As a consequence of this research a great necessity arises for the measuring of non-conventional functional properties such as: absorbance, humidity, corrosion, magnetical behaviour, wear and cycles resistance, material ageing and stability under changing operating conditions. This criterion is important for assessing the suitability of RM methods for final-industrial applications and is usually not included in academic research.

10.3.3 Web-based applications

There is a tendency to develop selection tools and KBE systems based on internet platforms, this facilitates the access for different users worldwide and helps introducing the system to potential users getting more feedback and possible uses, amendments, etc. This research has provided a pilot application made with Matlab on a dedicated system, however further research can be done on how to take this functionality to a web-based accessible system.

10.3.4 Additional data

Also there is an important need to standardize a number of properties of interest for RM: for instance the measure of mechanical properties, surface roughness, thermal properties, etc. This is an important task for gathering accurate and sufficient data for comparison, otherwise the comparison of competing processes and materials will be performed under the basis of unreliable data, thus guiding to bad results. Currently material data is being obtained by existing material testing standards; future research could be based on analyzing special requirements of RM and variations due to the additive nature of RM processes.

10.3.5 CAD plug-in

As described earlier, data regarding part measures and properties must be manually entered by the user. A common way to save time is by automating the process of feature and information extraction. There are a number of APIs already available which can be linked to conventional CAD packages and .STL viewers. The integration can be twofold: one is to integrate an API into the KBE system in order to communicate with a commercial CAD package and extract the features of interest. The second is the inverse, the integration of the KBE system into an open source viewer and editing software. The second option can be by far the most complex but would guide to a comprehensive design solution.

Appendix 1

Complete RP/ RM process classification

A complete RP/ RM process classification[1]

- POWDERS
- MELTING OF POWDER
- SINTERING WITH A HEAT TRANSFERRING LASER
    - Selective Laser Sintering (SLS) by DTM Corporation
    - SLS (Solid Imaging Solutions) by 3D Systems
    - Direct Plastic/Metal Laser Sintering (DMLS) by EOS
    - Selective Laser Sintering of Ceramics by Rheinisch-Westfälische Technische Hochschule Aachen
    - Selective Laser Reaction Sintering (SLRS) by University of Texas
    - Direct Metal Fabrication (DMF) by Rockwell Scientific
    - Compacted-powder SLS by The University of Manchester
- MELTING WITH A HEAT TRANSFERRING LASER
    - Laser Engineered Net Shaping (LENS) by Optomec/Sandia National Laboratories
    - Lasform by AeroMet
    - Direct Metal Deposition (DMD) by Precision Optical Manufacturing/The University of Michigan
    - Direct Light Fabrication (DLF) by Los Alamos National Laboratory
    - Controlled Metal Buildup (CMB) by Fraunhofer IPT
    - Direct Light Fabrication by University of Birmingham's School of Metallurgy and Materials
    - Laser Aided Direct Rapid Prototyping (LADRP) by University of Central Florida
    - Laser-aided Powder Solidification / Powder Jet (LAPS-J) by Institute für Strahlwerkzeuge (IFSW)
- USING CONVENTIONAL SINTERING AND HIP
- Freeform Powder Molding (FPM) by Rensselaer Polytechnic Institute (RPI)
- BINDING POWDER BY ADHESIVES
- METHODS BASED ON MIT's 3D PRINTING
    - 3D-Printing by Z Corporation
    - Direct Shell Production Casting (DSPC) by Soligen (1992-2004?)
    - Prometal by ExOne
- EXTRUSION OF CERAMICS WITH MELTED BINDER
    - Fused Deposition of Ceramics (FDC) by Rutgers University
- OTHER METHODS
    - Topographic Shell Fabrication (TSF) by Formus
    - Multiphase Jet Solidification (MJS) by Fraunhofer IFAM and Fraunhofer IPA

- SOLID MATERIALS
- EXTRUSION OF MELTED MATERIAL
- EXTRUSION OF PLASTICS
- Fused Deposition Modeling (FDM) by Stratasys
    - Melted Extrusion Manufacturing (MEM) by CLRF, Tsinghua University/Fang Ming Da Co.
- Contour Crafting (CC) by Dr. Khoshnevis, University of Southern California
- METHODS BASED ON WELDING
    - Shape Melting by Babcock & Wilcox
    - Shape Welding by Thyssen Ag
- 3D Welding by Cranfield University
    - Droplet Welding (DROW) by AeroChem Research Laboratory, Division of Titan Corp.
- SPRAYING OF METAL
    - Incremental Fabrication by Incre Inc.
    - Recursive Mask and Deposit MD* by Carnagie Mellon University
- EXTRUSION & MILLING OF MULTIPLE MATERIALS
    - Shape Deposition Manufacturing (SDM) by Carnegie Mellon University
- INKJET TECHNIQUES
    - Multi Jet Modeling by 3D Systems
    - 3D Plotting by Solidscape Inc. (formerly known as Sanders Prototype Inc.)
    - Ballistic Particle Manufacturing (BPM) by BPM
    - Liquid Metal Jetting by University of Texas
    - Photo Chemical Machining (PCM) by Texas Instruments

- SHEETS
- BOND-FIRST LAMINATION
- CUTTING MATERIAL WITH A LASER
    - Laminated Object Manufacturing (LOM) by Helisys Inc.
    - Curved-layer LOM by University of Dayton and Helisys Inc.
    - Laminated Object Manufacturing (LOM) by Landfoam Topographics
    - Slicing Solid Manufacturing (SSM) by CLRF, Tsinghua University
    - Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM) by CAM-LEM Inc.
    - LOM which uses ceramic material by Ceramic Composite Inc.
- CUTTING MATERIAL WITH A KNIFE
    - Paper Lamination Technology (PLT) by Kira Corporation
- CUTTING MATERIAL WITH A MILLING MACHINE
    - Layer Milling by Helsinki University of Technology / Pro Tooling Oy
- CUT-FIRST LAMINATION

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[1] Koukka, H. (2006). The whole RP family tree, Helsinki University of Technology. http://shatura.laser.ru/rapid/rptree/rptree.html (visited Feb 2008)

- CUTTING MATERIAL WITH A LASER
    - Laser Profiling Machine (LPM) by Liptool Ltd
- CUTTING MATERIAL BY WATER
    - TruSurf by Gilmore Engineers Pty Ltd
- CUTTING MATERIAL WITH A KNIFE
    - Offset Fabrication by Ennex Corporation
    - JP System 5 by Schroff Development Corporation
- CUTTING MATERIAL WITH A HEATED ELECTRODE
    - HotPlot by Sparx AB
- CUTTING MATERIAL WITH A MILLING MACHINE
    - Staratoconception by Charlyrobot / Cirtes

- GAS, ATOMS AND OTHER ODD STUFF
- MISCELLANEOUS
- GAS
    - Gas Phase Deposition (GPD) by University of Texas
    - Laser-Assisted Chemical Vapor Deposition (LCVD) by Georgia Institute of Technology
    - Selective Area Laser Deposition (SALD) by University of Connecticut
    - Selective Laser Reaction Sintering (SLRS) by University of Connecticut and University of Texas
    - Laser Assisted Selective Area Metal Organic Chemical Vapor Deposition (huh?) LASAMOCVD
- INDIVIDUAL ATOMS OR MOLECULES
    - Manipulation of individual atoms with a scanning tunnel microscope by Eigler and Schweizer, IBM Inc.
    - Molecular nanotechnology by Institute for Molecular Manufacturing

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- LIQUIDS
- PHOTOCURABLE LIQUIDS
    - CURING BY LIGHT THROUGH MASKS
        - Solid Ground Curing (SGC) by Cubital Inc.
        - Design-Controlled Automated Fabrication (DESCAF) by Light Sculpting
        - Rapid Micro Product Development (RMPD) by MicroTEC
        - Microstereolithography by Ecoles Polytechniques federale de Lausanne
    - CURING WITH A VISIBLE LIGHT LASER
        - Mark 1000 by Quadrax Laser Technologies Inc
    - CURING WITH AN UV-LASER (SINGLE BEAM)1
        - StereoLithography (SLA)2 by 3D Systems
        - Stereolithography by Aaroflex Inc.
        - Stereolithography by Russian Academy of Sciences
        - Stereos (Stereos line was sold to 3D System 1997)
        - Solid Laser Diode Plotter System (SLP) by Denken
        - Solid Creation System (SCS) by Sony/D-MEC
        - Soliform by Teijin-Seiki
        - UniRapid by Unirapid Inc.
        - Solid Object Ultra-Violet Laser Plotting (SOUP)
        - Air Bubble Stereolithography by Osaka Sangyo University
    - CURING WITH TWO LASER BEAMS SIMULTANEOUSLY
        - Holographic Interference Solidification by Quadtec
        - Beam Interference Solidification by Batelle Development Corporation
        - Photochemical Machining by Formigraphics Inc.
    - CURING BY VISIBLE LIGHT WITH A DVD-DEVICE
        - Direct Photo Shaping (DPS) by SRI International (1998-2001)
    - HYBRID, COMBINING INKJET-TECHNIQUE AND CURING WITH AN UV-LAMP
        - Objet 3D-printer by Objet Geometries Ltd.
    - ELECTRICAL CONDUCTING LIQUID (ELECTROLYTE)
    - ELECTROPLATING
- Electrochemical Fabrication (EFAB) by Information Science Institute, University of Southern California
    - FREEZING OF WATER
        - Rapid Freezing Prototyping (RFP) by University of Missouri – Rolla

Appendix 2

RP/ RM CHARACTERIZATION SPREADSHEET

	SLA	*SLS*	*FDM*	*3DP*	*Envisiontec*	*EBM*	SLM	OBJET Polyjet	DMLS	Laser Cusing	LENS
Nombre	ESTEREOLITOGRAFÍA	Sinterizado Selectivo Láser	Fused Deposition method	3D Printing	Perfactory	Electro Beam Melting	Selective Laser Melting	Objet Geometries	Direct metal laser sintering	Linear laser melting	Laser engineered Net Shaping
Mercados meta	modelos prototipo, master para moldes de silicona	piezas, IM, die casting, moldeo por soplado	modelos, prototipos funcionales, ciertos usos finales	prototipos, maquetas y comprobación visual	Estandar: diseño industrial y maquetas. Mini: Diseño de piezas pequeñas con buenos acabados para: joyeria, diseño	piezas finales de alta densidad, implantes	Estampado, aplicaciones generales de utillajes, partes directas, implantes médicos	modelos, prototipos funcionales, ciertos usos finales	IM, Die casting, partes directas, componentes para moldes(inyección, soplado, termoconformado)	IM, die casting, partes finales	IM, componentes aeroespaciales, médicos y de defensa
Fabricantes	3D Systems Electrolux, Sony, Mitsubishi-CMET, Teijin Seiki, Mitsui, EOS	EOS, 3D systems	Stratasys	3D systems, Object, Zcorp	EnvisionTec	Arcam	www.mcp-group.de	2objet	EOS www.info.info	concept laser	optomec
Descripción	Se basa en la acción de un láser UV que se proyecta sobre un baño de resina fotosensible líquida para polimerizarla. El láser recorre la geometría del producto capa por capa polimerizando la resina hasta copletar la figura final	Se deposita una capa de polvo, de unas décimas de mm., en una cuba que se ha calentado a una temperatura ligeramente inferior al punto de fusión del polvo. Seguidamente un láser CO2 sinteriza el polvo en los puntos seleccionados.	Una boquilla que se mueve en el plano XY horizontal deposita un hilo de material a 1ºC por debajo de su punto de fusión. Esta hilo solidifica inmediatamente sobre la capa precedente	Fabrica prototipos en base a polvo o resina mediante un cabezal movil que deposita gotas de aglutinante siguiendo el perfil capa a capa. Permite la obtención de distintos colores según el aglutinante utilizado. En el caso de la resina, esta se irá deponiendo en forma líquida gota a gota usando soportes de otro material	Usa la polimerización por lus natural para mejorar y abaratar el proceso.	Construcción de piezas funcionales mediante la fusión de metal en polvo depositado por capas. El uso de un cañon de electrones permite la fabricación de piezas 100% densas, gracias a la completa fusión del material.	Proceso directo basado en la fusión de polvo metálico aplicado en capas muy finas sobre una plataforma, mediante la acción de un láser. Una vez que la plataforma ha descendido y se ha recubierto con una nueva capa de polvo, el laser genera en cada capa el contorno de la pieza a construir fundiendo el polvo	Consiste en la impresión de un material fotosensible mediante un cabezal tipo inpresora depositado en capas de 16micras. Una vez depositado una lus UV solidifica el material, la bandeja desciende y el proceso se repite	Se basa en el principio de sinterizado laser de los equipos EOS para fabricar piezas en base a polvo metálico	Proceso directo basado en la fusión de polvo metálico aplicado en capas muy finas sobre una plataforma, mediante la acción de un láser. Una vez que la plataforma ha descendido y se ha recubierto con una nueva capa de polvo, el laser genera en cada capa el contorno de la pieza a construir fundiendo el polvo	Consiste en construir componentes por adición de polvo metálico usando un haz laser para fundirlo y solidificarlo.

Materiales disponibles	- Resinas fotosensibles de diferentes fabricantes que varían en propiedades de flexible y durable a rígido y duro. - 24 variedades de 3 fabricantes. - -	-Cualquier material que pueda sinterizarse o que se adhiera sin derretirse: PC, Cera para microfusión, Nylon, Nylon reforzado con fibra de vidrio, y polvos metálicos recubiertos de plástico. -	. ABS, cera de fundición, Elastómero, Poliester, Policarbonato - Se estima que las piezas por FDM tienen entre el 60% y 80% de la dureza del ABS inyectado. -PC: presenta mayor dureza y resistencia que el ABS. -	- Celulosa en estado sólido (polvo) pegada por un agente de unión, cera, laminas de PVC, Resina acrílica, Parafinas, Fotopolímeros	variety of materials will be available, including methacrylates, expoxydes, nanoparticle filled materials and compounds. Materials come in sealed and leak safe cartridges	Titanio, Aleaciones de cobalto- cromo, Acero inoxidable y algunas aleaciones en desarrollo como: Berilio, Titanio Aluminio, superaleaciones .	Construcción de piezas definitivas e insertos para moldes en casi todo tipo de metales y materiales cerámicos: Aleaciones de bajo punto de fusión, zinc, bronce, acero inoxidable, aceros para moldes, titanio, óxido de aluminio y carburo de silicio.	Fullcure 720(translucido), Fullcure 830, 840(azul y blanco para pequeños detalles), Fullcure 950, 970 (TangoGray, Tangoblack) simula la goma o caucho	Sólo polvos metálicos: Direct Metal 20, Direct Steel 20, Direct Steel H20, aceros tipo herramienta, acero inoxidable base bronce, superaleaciones	aceros inoxidables, aceros tipo herramienta, titanio, aluminio. Todos en polvo	metales en polvo incluyendo acero tipo herramienta, aceros inoxidables, titanio, inconel y otros
Aplicaciones finales	- Modelos para investment casting por Quikcast. - - Evaluaciones estéticas de forma, ajuste y ensamble. -	-Prototipos funcionales, geométricos, estéticos. - Utillajes prototipo y de preserie. -Rapid Manufacturing	Prototipos tangibles, funcionales o de montaje.	-Comprobación visual de ideas, bosquejos, maquetas e intenciones de diseño. -Etapas tempranas del proceso de diseño para varias interaciones.	Especial para joyería y mecanismos de tamaño reducido. Modelos de microfusión	Prototipos metálicos y piezas 100% funcionales en material final. Como: prototipos aeroespaciales, piezas para vehículos de carreras, implantes	Insertos de moldes, preseries, piezas finales en series cortas con alta densidad. Sheet metal press tools	Tiene un nicho importante en e mercado de la joyería	Prototipos (Estético-Geométrico-Funcional) - Tooling(prototipo-preserie) -RM	Moldeo por inyeccion, die casting y partes finales de alta densidad	artículos médicos de alta precisióm, piezas para industra aeronautica, reparación y anexión de detalles a piezas metálicas, producción en bajas series
Tipo de tecnología	Directa / Indirecta	Directa	Directa	Directa		Directa	Directa		Directa/Indirecta	Directa	Directa
Láser/ Tipo	No.Rayo de luz UV de 325 nm de longitud de onda, base He - Cd, - Rayo Nd YVO4	Si. 50W CO2, Nd YAG	No	No cabezal eyector tipo impresora	no	No. (cañón de electrones)	SI Nd, YAG, fiber		Yb fibre laser 200W	Diose-pùmped solid state laser. 100W	Nd- Yag
Potencia láser	100mW - 216mW	50W - 70W	-			EBM beam 3500W	100 - 300W cw		200W	100W	500W - 2kW

Diametro Láser (determina el espesor de paredes)	Ajustable Aprox 0,2 - 0,65mm profundidad típica de 0,5mm	10 - 500µm	-	4 cabezales de impresión, 1216 eyectores		-	50-20 µm		100 - 500µm		
Uso de soportes	Si. Filamentos de material fotosensible colocados en inervalos de aprox. 6,4mm	No. El mismo polvo actual como soporte. Cuidado para poder evacuarlo de toda la geometría.	Si. Dos tipos: BASS(Break away support Structures) y Waterworks (Watter soluble support structures)	No. El mismo polvo sin utilizar de la cámara actua como soporte. Utiliza en algunos modelos como Thermojet	si	Si. Para geometrías libres	si	Si	Si. Diseñados para geometrías libres y para la primera capa base sobre el sustrato de fabricación	Si	Si
Envolvente de trabajo mm	De 254 X 254 X 254 (SLA 250) hasta 1500 X 750 X 500mm (Viper Pro)	330 X 279 X 381mm hasta 300 X 300 X 600mm EOS 550 X 550 X 700 mm 3D systems	De 203 X 203 X 305mm(Prodigy Plus) hasta 599 X 500 X 599mm (Maxum)	203 X 254 X 203mm(Z406) hasta 508 X 610 X 406mm Z810	59x44x230 a 120x90x230	250 X 250 X 200 mm / Tamaño max de parte: 200 x 200 x 200	250 X 250 X 250	250x250x200 (Eden250) a 500x400x200(Eden 500v)	250 X 250 X 200mm	250 X 250 X 250mm(M3 Linear)- 350x 300x 280 M1 Cusing	300 X 300 X 300, 460 X 460 X 1056, 1500 X 900 X 900
Velocidad promedio	3,5 - 5m/s escaneo	10 -25 mm/hr (altura z) 2 - 20mm3/sec		0,18 - 0,4mm/min	. Independinetem	1cm3/min	5cm3 deacero denso por hora		2 - 20 mm3/seg		60mm/s Desposición a 0,5kg/hr
Espesor de capa tipico (mm)	0,05mm - 0,15mm (Viper Pro)	0,1 - 0,15mm (EOS)Depende del diámetro mínimo del láser, su diametro de radiación y el tamaño de grano. Los valores típicos son: PA11 0,80 [mm]	ABS 0,127mm 0,254mm - 0,330mm -PC 0,178mm - 0,254mm- 0,330mm	0,089 - 0,203 mm	0,1 - 0,5mm (50micras)	0,05 - 0,2 mm	30 µm . 20- 200µm	16micras a 30 micras en HQ mode	20 - 300µm	20µm	de 500micras con LENS 850-R a 0,002- 0,8mm M3D 300
Precio aproximado Dlls	95 000 - 370 000 E	300 000 - 400 000 E	150 000 - 250 000	20 000 - 70 000	35 000 - 120 000	519 000	250 000 - 270 000	50 000 - 150 000	160 000- 690 000	250 000 - 270 000	325 000- 995 000

Precisión dimensional / tolerancias	Ofrece la mayor precisión dimensional con la menor tasa de contracción del material (0.1%) tolerancias entre +/- 0,2 mm (0,5-1% medida nominal)	buena +/- 0,05 - 0,25 mm 0,5 - 1% Según DIN 16901.	0,2% de la medida nominal. +/- 0,127 - 0,35mm Iguala a la SLA y supera al SLS. Es más facil de controlar por ser afectada por menos parámetros	+/- 1-4% 0,635mm Pobre. Tiene las mayores variaciones de todas las tecnologías	+- 0,025mm	medias. +- 0,16% (+/- 0,3 - 0,4mm)	+/- 0,1 mm	0,2% de la nominal	medio +/- 0,02 - 0,07% + 50µm de la medida nominal	+/- 0,05mm	+/- 0,125mm / 0,25mm
Acabado superficial/ coef.rugosidad	Entrega el mejor acabado aun antes del pos proceso. La parte superior es la mas fina y en las laterales es visible el efecto escalonado	7.5 a 50 RaµmTodas las superficies presentan acabados rugosos y porosos.	Deficiente. Acabados rugosos y porosos comparados con SLS y 3DP.	Acabado rugoso y con texturas. Se ha caracterizado como similar al nivel 150 de un lija		10 a 20 Ra µm - Tiende a tener un acabdo similar a las piezas de fundición. Posibilidad de post-procesado. Estética mala	< 10 Ra µm. Justo despues de la fabricacion presenta una rugosidad de approx. 10-30 µm for Rz.	Muy alta calidad	Bruto Ra 9-11; Granallado Ra 3-5, 3 despues de shot peening	4,5 - 7Raµm despues de laser cusing.	granos finos 5,1 a 7,6Raµm
Definición / Detalle	capaz de producir detalles de hasta 0,25mm dependiendo entre otros del diámetro del láser	Tipicamente 0.64mm - 1mm dictado por el diámetro del láser y la fusión del material que rodea el detalle	Los detalles mínimos se limitan al doble del espesor de capa. Entre 0,41 - 0,61mm	Con una resolución de 600dpi 0,10-0,15mm. Aunque debido a las etapas de infiltración y limpieza de polvo se limita a : 0,76- 1,52mm	0.15 - 0.25mm	malo 0,25mm	< 0,2. Es posible proyectar los detalles mas finos como paredes verticales de menos de 100 µm		Nivel medio-bajo Usualmente hasta 0,3 - 0,6mm	hasta 0,4mm	0,51mm (Requieren acabado)

Vida de la herramienta (Si se usa para tooling	decenas. Tienen mala conductividad por tanto se enfrian en mayor tiempo con pérdida de propiedades de fuerza(Tensile) pero ganancia en el modulo de flexión de las piezas.	si. Im = 100 000 a 500 000. Die casting > 500		Con ZCast se pueden crear modes de arena para materiales no-ferrosos como el aluminio. Tambien es posible hacer piezas para Investment casting con un material mezcla de celulosa y escayola		Si, IM> 1 millón, Die casting Al, Zn > 100 000	estampado metálico > 3000, IM >100 000 a 250 000. Die casting 1000 a 5000. EPS>500 000		Si. IM> 1 millon, zinc die casting >5000, alum die casting >1000	IM > 1 millón	IM > 1 millon
Densidad de pieza final	100%	98 a 100%				100%	99 - 100%		acero/superaleaciones aprox 100%, base bronce aprox 93%	99 - 100%	99 - 100%
Maquinabilidad	Es posible. En operaciones como fresado, taladrado y forjado deben tomarse precauciones para evitar rompimientos. -Tambien acabados como arenado, pulido de superficies y acabados estéticos.	Fácilmente maquinables. Aunque las piezas hechas en PA pueden derretirse por el calentamiento en ciertas áreas. -Para sinterizado de metales tiene buenas propiedades para el pulido, obteniéndose acabados espejo. Acabado de máquina, CNC, electroerosión, pulido manual, trapo, etc.	Facilmente sin mayores problemas. Pueden ensayarse, mecanizarse y recibir tratamientos posteriores (arenado, deposiciones metálicas, impresiones, pintura). Dado que usa termoplasticos, las piezas de FDM pueden soldarse ultrasonicamente	No maquinables; aunque con la apropiada selección de algún infiltrante sería posible		Puede aplicarse cualquier proceso de maquinado convecional: CNC, MAV, EDM	total		Puede aplicarse cualquier proceso de maquinado convecional: CNC, MAV, EDM	Resultan aceros tipo herramienta de alto grado de hasta 54 Rc despues de tratamiento térmico	

Resistencia Mecánica / Térmica	Resistencia mecánica y térmica buenas (para prototipos). No deben ser expuestas a suciedad, calor sobre 46c o agentes químicos. Incluso la humedad o inmersión en agua es dañina	Presentan las mismas propiedades de los termoplásticos en que se basan. Resiste suciedad, calor hasta 163c y muchos químicos: ácidos, bases. Alcohol, hydrocarburos, etheres, etc.	R mecánica alta, y R térmica media. Similar al SLS, ofrece las propiedades de sus materiales base. Con ABS soporta temperaturas hasta los 93c y agentes químicos como petroleo, gas, aceite, ácidos.	deben limitarse a un entorno controlado por se suceptibles a absorver suciedad. Al ser infiltrados asumen las propiedades de la sustancia infiltrada.		Mecánica y térmica excelentes, igual que en los procesos convencionales			R mecánica alta. -R térmica media. Piezas en acero se comparan con partes de acero convencional; basadas en bronce se comparan con las piezas de aluminio		Es posible obtener metales y aleaciones sólidas y también estructuras materiales gradientes. Alta resistencia y buena ductilidad y dureza
Canales de refrigeración	SI, siempre que sea posible extraer la resina líquida sin quedar atrapada	Si	-	-	-	si	si	-	sin problemas (el polvo sin sinterizar fluye fuera de los canales de la pieza	Si	posible. Tambíen es posible incluir materiales predefinidos al proceso (embeded materials)
Capacidad multimaterial	no	no	si	si	si	si	si	si	si, limitada	no	Si, incluye la capacidad de materiales gradientes con buen control
partes multiples?	Si	Si	SI. No hay economía de tiempo en construir múltiples partes. El tiempo permanece igual para cada una.	SI	Si	SI	si		si	si	si

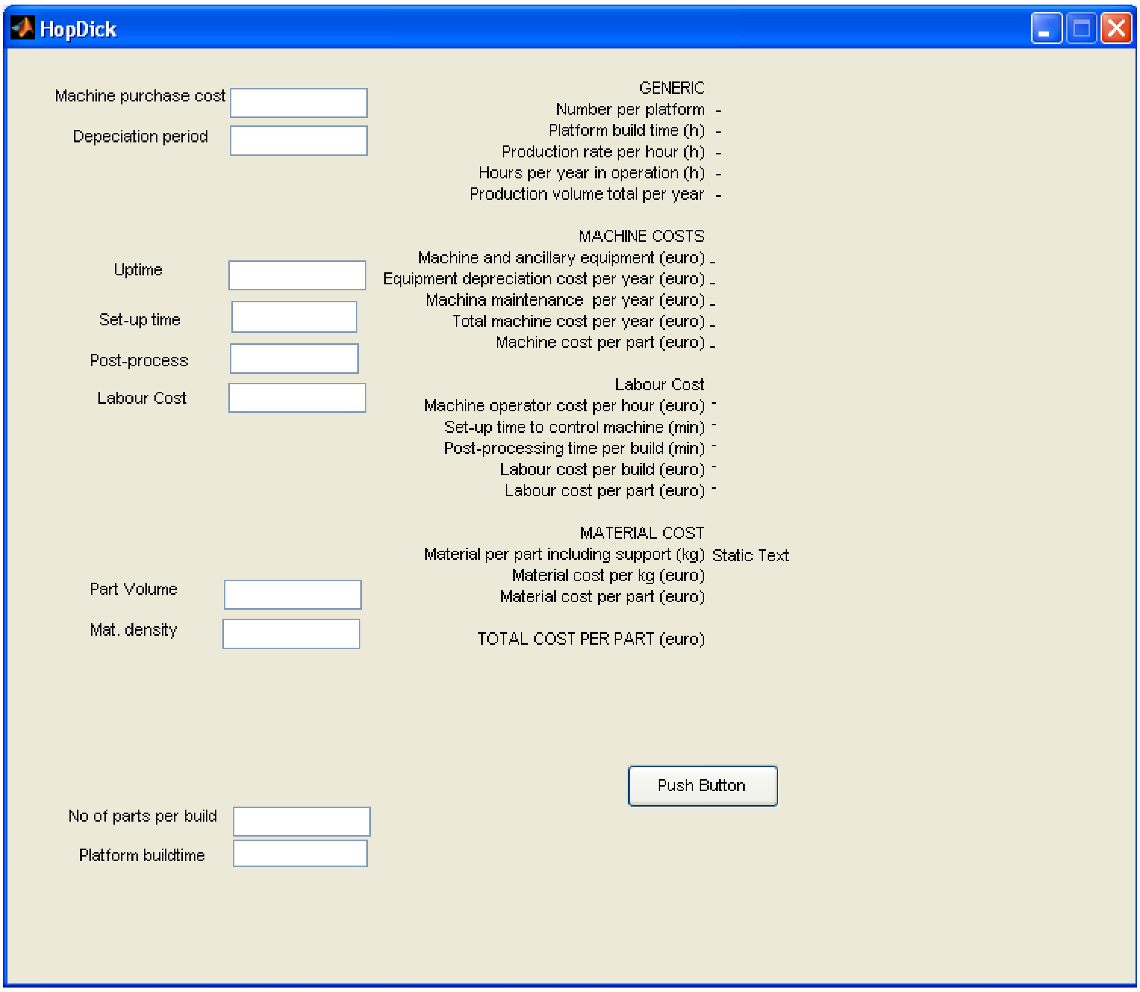
Appendix 3

Matlab Code for Hopkinson & Dickens model

Matlab Code for Wilson model

Matlab code for Dickens' model

MatLab code for the Hopkinson-Dickens method for RM cost estimation

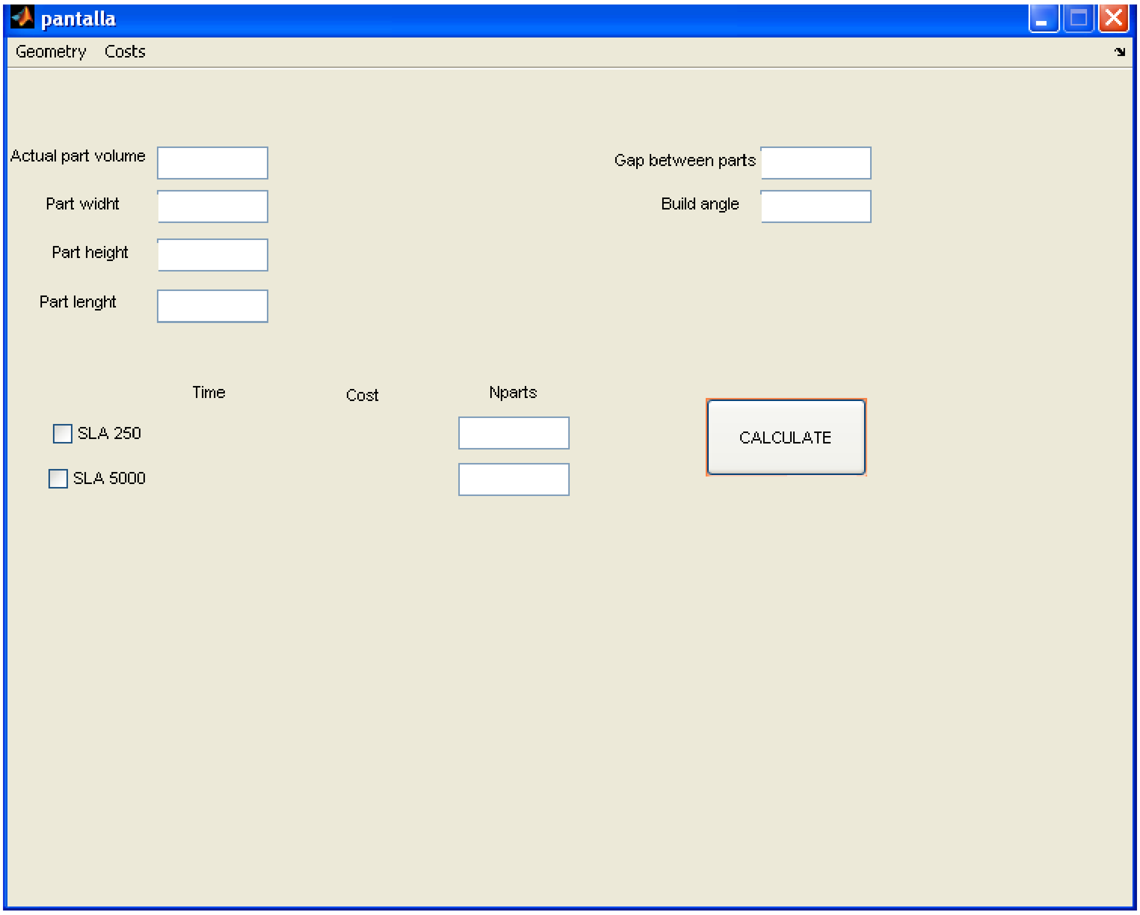


```
function pushbutton1_Callback(hObject, eventdata, handles)
global E  De PartVol density Op T N Post Set uptime
%Materialcosts
%---------------------------------------------
% ESTEREOLITOGRAFIA
R = N/T;
HY = (365*24*uptime)/100;
V = R*HY
 % MATERIAL
SLcost = 275.20  % en (kg)
%peso de la parte
SLMass = PartVol * density;
% coste per kg
% Coste de material per part para SLS
SLMCP = SLMass * SLcost;
 %MACHINE COSTS
%Purchase cost
M = .0856 * E;
D= E/8;
% Machine cost per year
MC = D+M;
% Machine cost per part
MCP = MC/V;
 % LABOUR COSTS
%operator cost
Seth=Set/60;
Posth=Post/60;
```

```
L = Op * (Seth+Posth);
LCP = L/N

Total_cost = (LCP+ SLMCP + MCP);
set(handles.text13, 'String', Total_cost);
vector1=[N;T;R;HY;V];
vector2=[E; D; M; MC;MCP];
vector3=[Op;Set; Post; L; LCP];
vector4=[SLMass;SLcost; SLMCP];

set(handles.text14, 'String', vector1);
set(handles.text15, 'String', vector2);
set(handles.text16, 'String', vector3);
set(handles.text17, 'String', vector4);

function edit5_Callback(hObject, eventdata, handles)
global PartVol
PartVol = str2double(get(hObject, 'String'));
if isnan(PartVol)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end
% Save the new density value
handles.metricdata.PartVol = PartVol;
guidata(hObject,handles)
% --- Executes during object creation, after setting all properties.
function edit5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

 function edit6_Callback(hObject, eventdata, handles)
global density
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
density = str2double(get(hObject, 'String'));
if isnan(density)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end
% Save the new density value
handles.metricdata.density = density;
guidata(hObject,handles)
% Hints: get(hObject,'String') returns contents of edit6 as text
%        str2double(get(hObject,'String')) returns contents of edit6 as a
double

% --- Executes during object creation, after setting all properties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit7_Callback(hObject, eventdata, handles)
global Set
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
Set = str2double(get(hObject, 'String'));
if isnan(Set)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end
% Save the new density value
handles.metricdata.Set = Set;
guidata(hObject,handles)
% Hints: get(hObject,'String') returns contents of edit7 as text
function edit7_CreateFcn(hObject, eventdata, handles)

function edit8_Callback(hObject, eventdata, handles)
global Post
Post = str2double(get(hObject, 'String'));
if isnan(Post)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end

function edit9_Callback(hObject, eventdata, handles)
global N
N = str2double(get(hObject, 'String'));
if isnan(N)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end
% Save the new density value
handles.metricdata.N = N;
guidata(hObject,handles)

function edit10_Callback(hObject, eventdata, handles)
global T
T = str2double(get(hObject, 'String'));
if isnan(T)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end

function edit11_Callback(hObject, eventdata, handles)
global Op
Op = str2double(get(hObject, 'String'));
if isnan(Op)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end


function edit12_Callback(hObject, eventdata, handles)
global uptime
uptime = str2double(get(hObject, 'String'));
if isnan(uptime)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end

function edit12_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

MatLab code for the Wilson method for RM cost estimation



```
function pushbutton1_Callback(hObject, eventdata, handles)
global Volume Lvat Hvat Wvat
vol_part= 94000000
Lpart= 300
Hpart= 300
Wpart= 250
L_vat = 400
H_vat = 400
W_vat =500

Vbb= Lpart* Hpart * Wpart;
Vjump=2*Vscan;
%% CALCULO DE TIEMPOS
%antes...  phi alpha
Fphi=(phi*(e.^(alpha*(1-phi))));
Zpart=height;
%antes: Zpart
Aavg= (Vbb * Fphi)/Zpart;
lpart=lenght;
Vavg= (Vscan * Fphi)+ (Vjump*(1-Fphi));
Zsupp= Zsupp_min + ((lpart*sin(teta))/2);
Ztotal=(lpart*sin(teta))+ (Zpart*cos(teta));
Ztotal=Zheight;
%Aavg = Aact*(phi*(e.^(alpha*(1-phi))))/phi;
tdraw= (((Nscan* Aavg)/(Dscan * Vavg * Hatch))*(Zheight/tlayer))+
(((Nscan_supp * Aavg* supp_factor)/(Dscan* Vavg * Hatch))*(Zsupp/tlayer));
 %segunso mayor
tdelay = (Ztotal/tlayer)*(tdraw_delay + tstg_down + tstg_delay+
tstg_up+tsweep+ tswp_delay);
```

```
%Main formula 1 ----------------------------------
tbuild= tdraw + tdelay + tstartup;

%% CALCULO PARA MULTIPLES PARTES
Nbuild= (L_vat/(Lpart+gap))*(W_vat/Wpart+gap)*(H_vat/Hpart+gap);
tscan=((Nbuild*Nscan*Aavg/Dscan*Vavg*Hatch)*(Zheight/tlayer))+
((Nbuild*Nscan_supp*Aavg*supp_factor/Dscan*Vavg*Hatch)*(Zsupp/tlayer));

%COST CALCULATOR
Nppd=Nbuild*tbuild;
Cmaterial=(vol_part*dens*(1+supp_factor))*MatC;
Cmaintenance=(MaintC*Nmach)/365*Nppd;
Cmachine=(MachC*Nmach)/(365*ul*Nppd);

Clabor=(tpreproc+tprostproc)*tech_rate;
Cbuild=tbuild*Mach_rate;
Coperation=Cbuild+Clabor;
Ctotal=Cmaterial+Cmaintenance+Cmachine+Coperation;
```

MatLab code for the Ruffo method for RM cost estimation (only SLS)

```
function res= Ruffo (Part)
global part %Modelo de Ruffo para calculo de costes en SLS
for uw=1 :20
x =Part(uw,1);
y = Part(uw,2);
z = Part(uw,3);
VB = Part(uw,4);
Vext = Part(uw,5); %volume of the minimum geometrical box
Vbed = Part(uw,6); %volume of the entire machine bed

Cr= VB/Vext;
Prext= Vext/Vbed;
if  Cr< 0.4
    teta= (0.3422*(Cr.^2))+( 0.2468*Cr)+ 0.45;
elseif Cr> 0.4
    teta=(0.417*(2.71.^(0.9283*Cr)));
end

%teta*z*(0.042*(x.^(-.1809))*x*y)+(180-120*(Vext/Vbed)*z+400+3600;
a= (180-(120*Prext))*z+400;
c= 3600;
b= teta*z*(x*y* 0.042*(x.^(-.1809)));
tB(uw)=(a+b+c);
res=tB;
%disp(Cr);
%disp(teta);
end
```

Appendix 4

Sample parts information and geometrical info

Normalized (Norm)

MAX	379.44		345.92		410.99		282.33		15670.7		32749663.8	1		31.55	199
No	**x**	**Norm**	**y**	**Norm**	**z**	**Norm**	**Altura**	**Norm**	**Volume**	**Norm**	**Vbox**	**Norm**	**Vol/Vbox**	**Time SLS (hrs)**	**Time SLM (hrs)**
1	74.04	0.19513	50.49	0.14596	29.41	0.07156	29.79	0.10551	54.4	0.00347	109942.803	0.003357	0.49480274	2.9825	11.870
2	59.59	0.157047	211.82	0.61234	54.24	0.13197	54.93	0.19456	94.22	0.00601	684636.47	0.020905	0.13762048	4.3039	40.000
3	17.07	0.044987	128.05	0.37017	66.05	0.16071	66.88	0.23689	64.79	0.00413	144372.982	0.004408	0.44876818	4.9342	14.900
4	69.48	0.183112	52.11	0.15064	16.8	0.04088	17.02	0.06028	34.3	0.00219	60826.127	0.001857	0.56390242	2.3161	2.634
5	147.42	0.38852	107.72	0.3114	16.53	0.04022	16.71	0.05919	128.13	0.00818	262497.762	0.008015	0.48811845	2.3156	18.900
6	150.25	0.395978	124.72	0.36055	58.54	0.14244	59.16	0.20954	36.53	0.00233	1096991.6	0.033496	0.03330016	4.5386	41.000
7	18.23	0.048044	26.34	0.07614	35.26	0.08579	35.71	0.12648	5.56	0.00035	16931.0833	0.000517	0.32839009	2.8908	1.000
8	100.54	0.264969	21.79	0.06299	21.07	0.05127	21.35	0.07562	10.44	0.00067	46159.4523	0.001409	0.22617253	2.5383	1.006
9	142.59	0.375791	134.95	0.39012	151.56	0.36877	152.98	0.54185	187.59	0.01197	2916396.41	0.089051	0.06432253	9.4867	50.450
10	167.72	0.44202	67.25	0.19441	47.59	0.11579	48.1	0.17037	39.59	0.00253	536775.7	0.01639	0.0737552	3.9542	44.000
11	28.31	0.07461	56.74	0.16403	47.91	0.11657	48.52	0.17186	9.71	0.00062	76958.2834	0.00235	0.12617225	3.9667	2.126
12	84.66	0.223118	99.2	0.28677	36.18	0.08803	36.57	0.12953	27.96	0.00178	303849.481	0.009278	0.09201925	3.3531	4.614
13	56.54	0.149009	115.17	0.33294	39.42	0.09591	39.84	0.14111	70.81	0.00452	256691.679	0.007838	0.27585623	3.5131	12.730
14	51.62	0.136043	34.15	0.09872	12.05	0.02932	12.21	0.04325	6.13	0.00039	21242.0172	0.000649	0.288579	2.0617	1.000
15	107.02	0.282047	127.49	0.36855	149	0.36254	150.8	0.53413	205.31	0.0131	2032952.99	0.062076	0.10099102	7.3978	139.704
16	45.9	0.120968	91.81	0.26541	86.13	0.20957	87.21	0.30889	94.5	0.00603	362958.624	0.011083	0.26036026	5.0150	37.188
17	51.66	0.136148	126.07	0.36445	10.56	0.02569	10.7	0.0379	8.93	0.00057	68774.9167	0.0021	0.12984385	1.9856	1.000
18	135.74	0.357738	132.08	0.38182	25.72	0.06258	26.02	0.09216	24.52	0.00156	461122.028	0.01408	0.05317464	4.4803	2.879
19	35.52	0.093612	35.52	0.10268	47.47	0.1155	48.08	0.1703	56.03	0.00358	59891.4939	0.001829	0.93552517	3.6139	12.156
20	80.41	0.211918	80.41	0.23245	77.77	0.18923	78.75	0.27893	119.25	0.00761	502842.785	0.015354	0.23715166	6.2733	42.375
21	203.72	0.536896	85.42	0.24694	82.62	0.20103	83.53	0.29586	79.66	0.00508	1437733.61	0.043901	0.05540665	5.8275	30.025
22	82.69	0.217926	99.47	0.28755	22.97	0.05589	23.24	0.08232	16.06	0.00102	188932.254	0.005769	0.08500401	2.6436	1.684
23	72.29	0.190518	72.29	0.20898	69.92	0.17013	70.8	0.25077	10.99	0.0007	365391.019	0.011157	0.03007737	5.1369	3.511
24	312.71	0.824136	312.71	0.904	136.51	0.33215	71.96	0.25488	183.2	0.01169	13348977.6	0.407607	0.0137239	5.2150	59.486
25	354.43	0.934087	330.33	0.95493	235.32	0.57257	235.32	0.83349	243	0.01551	27550997.8	0.84126	0.00882001	6.6619	99.000
26	324.8	0.855998	345.92	1	129.57	0.31526	129.57	0.45893	501.28	0.03199	14557813.5	0.444518	0.03443374	5.7528	133.000
27	95.23	0.250975	101.58	0.29365	98.47	0.23959	99.15	0.35118	55.96	0.00357	952545.941	0.029086	0.05874782	6.6619	25.036
28	88.57	0.233423	102.28	0.29568	80.76	0.1965	81.32	0.28803	7.43	0.00047	731599.962	0.022339	0.01015582	5.7158	2.726
29	57.27	0.150933	57.57	0.16643	55.43	0.13487	56.13	0.19881	9.24	0.00059	182754.589	0.00558	0.05055961	4.3717	2.340
30	50.55	0.133223	50.93	0.14723	48.63	0.11832	48.63	0.17225	61.05	0.0039	125198.494	0.003823	0.48762567	4.0042	13.396
31	149.91	0.395082	149.91	0.43337	145.05	0.35293	146.58	0.51918	9.6	0.00061	3259709.82	0.099534	0.00294505	10.2031	6.350
32	12.85	0.033866	12.85	0.03715	12.43	0.03024	12.59	0.04459	0.04	2.6E-06	2052.47268	6.27E-05	0.01948869	2.0728	1.000
33	83.47	0.219982	83.57	0.24159	81.34	0.19791	82.23	0.29125	18.18	0.00116	567394.32	0.017325	0.03204121	5.7467	6.746
34	244.98	0.645636	114.74	0.3317	105.11	0.25575	106.06	0.37566	382.87	0.02443	2954537.54	0.090216	0.12958712	7.0169	101.000
35	153.6	0.404807	130.94	0.37853	95.77	0.23302	96.52	0.34187	848.39	0.05414	1926163.02	0.058815	0.44045597	6.5167	143.000
36	94.19	0.248234	98.29	0.28414	32.04	0.07796	32.27	0.1143	54.94	0.00351	296624.241	0.009057	0.1852175	3.1256	8.000
37	81	0.213472	24	0.06938	5	0.01217	5	0.01771	3.11	0.0002	9720	0.000297	0.31995885	1.6800	3.500
38	297.18	0.783207	235.48	0.68074	261.97	0.63741	263.33	0.9327	3885.72	0.24796	18332646.6	0.559781	0.2119563	12.1367	124.000
39	101.16	0.266603	101.16	0.29244	32.96	0.0802	33.07	0.11713	12.78	0.00082	337291.071	0.010299	0.03789012	3.1711	1.907
40	186.05	0.490328	170.21	0.49205	74.3	0.18078	74.51	0.26391	407.39	0.026	2352900.49	0.071845	0.17314374	5.9000	136.969
41	257.96	0.679844	64.49	0.18643	67.57	0.16441	68.19	0.24153	612.7	0.0391	1124083.74	0.034324	0.54506616	5.0383	135.000
42	69.11	0.182137	69.11	0.19979	19.1	0.04647	19.34	0.0685	57.69	0.00368	91225.2691	0.002786	0.63239057	2.4433	5.034

43	69.81	0.183982	92.71	0.26801	67.51	0.16426	68.25	0.24174	41.88	0.00267	436930.465	0.013342	0.09585049	5.5508	12.898
44	54.74	0.144265	54.74	0.15824	34.94	0.08501	35.33	0.12514	34.15	0.00218	104696.578	0.003197	0.32618067	3.2794	5.444
45	178.24	0.469745	235.81	0.68169	130.62	0.31782	132.22	0.46832	2957.22	0.18871	5490059.75	0.167637	0.53864988	10.9797	156.000
46	162.95	0.429449	296.46	0.85702	100.77	0.24519	101.96	0.36114	245.32	0.01565	4868012.98	0.148643	0.05039428	7.1650	112.866
47	73.33	0.193258	154.49	0.44661	32.95	0.08017	33.38	0.11823	51.15	0.00326	373282.369	0.011398	0.13702763	3.1908	7.704
48	112.84	0.297386	122.34	0.35367	108.9	0.26497	110.05	0.38979	121.1	0.00773	1503347.69	0.045904	0.08055355	7.5469	60.136
49	151.49	0.399246	91.18	0.26359	22.84	0.05557	23.13	0.08193	86.38	0.00551	315485.681	0.009633	0.27380006	2.6406	9.015
50	56.79	0.149668	105.6	0.30527	62.58	0.15227	63.34	0.22435	37.81	0.00241	375293.762	0.011459	0.10074774	4.7475	10.806
51	96.97	0.255561	94.5	0.27318	91.7	0.22312	92.68	0.32827	116.47	0.00743	840308.081	0.025659	0.13860393	6.2981	48.708
52	18.22	0.048018	31.75	0.09178	41.12	0.10005	41.64	0.14749	3.93	0.00025	23787.3032	0.000726	0.16521419	3.6033	1.000
53	185.57	0.489063	205.27	0.5934	69.85	0.16996	70.73	0.25052	99.23	0.00633	2660722.98	0.081244	0.03729437	5.1397	31.670
54	45.49	0.119887	33.81	0.09774	24	0.0584	24.31	0.0861	4.76	0.0003	36912.4056	0.001127	0.12895394	2.6972	5.850
55	173.71	0.457806	15.28	0.04417	115.39	0.28076	15.47	0.05479	24.12	0.00154	306278.385	0.009352	0.07875188	2.2306	1.684
56	111.61	0.294144	28.25	0.08167	63.5	0.1545	28.62	0.10137	25.25	0.00161	200214.389	0.006113	0.12611481	2.9208	21.000
57	7.23	0.019054	18.22	0.05267	7.23	0.01759	7.23	0.02561	0.14	8.9E-06	952.412238	2.91E-05	0.14699517	2.4000	1.500
58	138.43	0.364827	138.53	0.40047	130	0.31631	131.59	0.46609	308.13	0.01966	2492972.03	0.076122	0.12359946	8.3458	144.000
59	96.22	0.253584	111.64	0.32273	32	0.07786	32.41	0.11479	21.69	0.00138	343744.026	0.010496	0.06309928	3.123	3.172
60	183.83	0.484477	196.98	0.56944	171.45	0.41716	171.45	0.60727	944.23	0.06025	6208347.39	0.18957	0.15209039	10.588	99.000
61	85.53	0.225411	125.24	0.36205	53.17	0.12937	53.85	0.19073	95.61	0.0061	569545.194	0.017391	0.16787079	4.251	23.232
62	143.28	0.377609	159.95	0.46239	22.21	0.05404	22.49	0.07966	45.2	0.00288	509000.696	0.015542	0.08880145	2.623	4.587
63	78.79	0.207648	91.92	0.26573	38.1	0.0927	38.59	0.13668	154.15	0.00984	275934.556	0.008426	0.55864696	3.456	26.842
64	78.79	0.207648	203.54	0.5884	38.1	0.0927	38.59	0.13668	380.56	0.02428	611006.522	0.018657	0.62284114	3.477	66.267
65	61.72	0.162661	33.52	0.0969	10.67	0.02596	10.81	0.03829	5.08	0.00032	22074.6764	0.000674	0.23012795	1.983	1.000
66	34.27	0.090317	51.84	0.14986	10.16	0.02472	10.29	0.03645	4.82	0.00031	18049.8171	0.000551	0.26703872	1.962	1.000
67	50.52	0.133144	180.42	0.52157	34.9	0.08492	35.34	0.12517	123.09	0.00785	318107.162	0.009713	0.38694508	3.292	19.629
68	76.42	0.201402	76.52	0.22121	66.9	0.16278	67.74	0.23993	11.87	0.00076	391208.347	0.011945	0.03034189	4.981	3.628
69	87.57	0.230787	83.08	0.24017	147.65	0.35925	81.36	0.28817	227.27	0.0145	1074200.35	0.0328	0.21157133	5.700	83.436
70	57.19	0.150722	36.03	0.10416	112.18	0.27295	36.5	0.12928	11.26	0.00072	231153.138	0.007058	0.0487123	3.335	1.855
71	146.23	0.385384	168.73	0.48777	108.79	0.2647	110.13	0.39008	670.3	0.04277	2684217.87	0.081962	0.24971892	7.208	144.000
72	157.58	0.415296	91.92	0.26573	76.2	0.18541	77.16	0.2733	132.39	0.00845	1103738.22	0.033702	0.11994692	5.475	70.733
73	274.51	0.723461	164.71	0.47615	29.73	0.07234	30.12	0.10668	51.74	0.0033	1344228.34	0.041046	0.03849048	3.022	7.032
74	229.45	0.604707	163.21	0.47181	39.77	0.09677	40.27	0.14263	82.73	0.00528	1489328.22	0.045476	0.05554853	3.553	15.033
75	54.1	0.142579	78.79	0.22777	78.79	0.19171	54.78	0.19403	259.45	0.01656	335845.448	0.010255	0.77252796	5.000	64.132
76	278.57	0.734161	91.29	0.2639	75.81	0.18446	76.76	0.27188	126.86	0.0081	1927897.98	0.058868	0.06580224	5.455	43.940
77	237.82	0.626766	83.75	0.24211	44	0.10706	44.56	0.15783	373.37	0.02383	876366.7	0.02676	0.42604312	3.750	75.073
78	36.19	0.095377	20	0.05782	36.19	0.08806	20.26	0.07176	4.79	0.00031	26194.322	0.0008	0.18286406	2.485	1.000
79	76.6	0.201876	245.71	0.71031	94.61	0.2302	77.57	0.27475	291.52	0.0186	1780691.33	0.054373	0.1637117	5.560	102.038
80	179.91	0.474146	166.22	0.48052	245.27	0.59678	248.1	0.87876	1831.81	0.11689	7334711.1	0.223963	0.24974535	14.630	123.000
81	57.01	0.150248	15.04	0.04348	192.81	0.46914	15.24	0.05398	49.63	0.00317	165321.155	0.005048	0.30020356	2.210	3.413
82	89.54	0.235979	93.68	0.27081	91.5	0.22263	92.64	0.32813	386.68	0.02468	767511.809	0.023436	0.50380984	6.280	161.640
83	170.17	0.448477	36.58	0.10575	13.02	0.03168	13.19	0.04672	17.56	0.00112	81047.1382	0.002475	0.21666404	2.111	1.045
84	68.54	0.180635	77.55	0.22418	66.35	0.16144	67.19	0.23798	43.03	0.00275	352668.629	0.010769	0.12201255	4.951	13.046
85	210.11	0.553737	210.11	0.60739	101.6	0.24721	102.86	0.36433	1832.9	0.11696	4485255.15	0.136956	0.40865011	6.903	110.000
86	66.18	0.174415	88.92	0.25705	12.5	0.03041	12.66	0.04484	11.95	0.00076	73559.07	0.002246	0.16245447	2.089	1.000
87	66.18	0.174415	88.92	0.25705	14.5	0.03528	14.69	0.05203	13.07	0.00083	85328.5212	0.002605	0.1531727	2.199	1.000

88	236.37	0.622944	210.11	0.60739	228.6	0.55622	231.26	0.81911	7766.55	0.49561	11353122	0.346664	0.68408936	16.144	123.000
89	379.44	1	166.75	0.48205	188.96	0.45977	166.75	0.59062	367.7	0.02346	11955805.3	0.365067	0.03075493	20.750	156.000
90	233.09	0.6143	275.77	0.79721	106.68	0.25957	106.68	0.37786	483.16	0.03083	6857308.18	0.209386	0.07045913	7.143	134.000
91	286.54	0.755166	200.26	0.57892	114.3	0.27811	115.71	0.40984	2510.87	0.16023	6558819.8	0.200271	0.38282345	8.183	199.000
92	140.44	0.370124	189.1	0.54666	88.84	0.21616	89.94	0.31856	1088.07	0.06943	2359342	0.072042	0.46117519	6.149	189.000
93	136.94	0.3609	173.29	0.50095	76.2	0.18541	77.16	0.2733	850.4	0.05427	1808251.34	0.055214	0.4702886	5.486	169.000
94	178.67	0.470878	155.94	0.4508	50.8	0.1236	51.44	0.1822	400.23	0.02554	1415379.43	0.043218	0.28277223	4.150	92.899
95	90.54	0.238615	80.35	0.23228	147.65	0.35925	81.36	0.28817	227.48	0.01452	1074137.36	0.032798	0.21177925	5.700	83.513
96	166.29	0.438251	166.24	0.48057	56.15	0.13662	56.86	0.2014	45.22	0.00289	1552213.39	0.047396	0.02913259	4.405	11.602
97	62.16	0.16382	148.65	0.42972	117.98	0.28706	62.95	0.22297	268.53	0.01714	1090145.11	0.033287	0.24632501	4.730	76.276
98	35.14	0.09261	35.14	0.10158	40.5	0.09854	41.02	0.14529	10.84	0.00069	50010.1938	0.001527	0.21675581	3.570	2.006
99	83.95	0.221247	54.85	0.15856	53.05	0.12908	53.72	0.19027	96.13	0.00613	244277.08	0.007459	0.39352853	4.239	23.302
100	113	0.297807	31.33	0.09057	13.53	0.03292	13.7	0.04852	22.23	0.00142	47900.1237	0.001463	0.46409066	2.140	1.374
101	165.92	0.437276	112.83	0.32617	165.92	0.40371	114.22	0.40456	47.82	0.00305	3106147.44	0.094845	0.01539528	7.442	24.646
102	123.56	0.325638	123.56	0.35719	38	0.09246	38	0.13459	147.6	0.00942	580148.797	0.017715	0.25441749	3.466	25.309
103	87.24	0.229918	105.19	0.30409	27.44	0.06677	27.79	0.09843	25.82	0.00165	251810.722	0.007689	0.10253733	2.879	3.238
104	64.92	0.171094	38.36	0.11089	51.37	0.12499	38.36	0.13587	12.77	0.00081	127928.314	0.003906	0.09982153	4.161	2.210
105	69.85	0.184087	141.85	0.41007	114.04	0.27748	70.73	0.25052	369.65	0.02359	1129933.69	0.034502	0.32714309	5.133	117.976
106	282.33	0.74407	282.24	0.81591	410.99	1	282.33	1	15670.7	1	32749663.8	1	0.47849957	31.550	160.000
107	237.82	0.626766	83.75	0.24211	44	0.10706	44	0.15585	373.37	0.02383	876366.7	0.02676	0.42604312	3.750	74.129
108	47.74	0.125817	47.76	0.13807	38.1	0.0927	38.59	0.13668	14.28	0.00091	86870.3774	0.002653	0.16438285	3.460	2.487
109	63.28	0.166772	34.5	0.09973	63.55	0.15463	34.94	0.12376	38.92	0.00248	138739.818	0.004236	0.28052509	4.016	6.136
110	98.91	0.260674	109.84	0.31753	138.62	0.33728	139.86	0.49538	49.1	0.00313	1506005.72	0.045985	0.0326028	8.801	30.987
111	54.84	0.144529	36.19	0.10462	24	0.0584	24.31	0.0861	20.56	0.00131	47631.8304	0.001454	0.43164413	2.688	2.255
112	76.16	0.200717	66.94	0.19351	36.66	0.0892	37.13	0.13151	37.49	0.00239	186898.194	0.005707	0.20059049	3.483	6.281
113	140.47	0.370203	140.47	0.40608	96.06	0.23373	97.15	0.3441	165.59	0.01057	1895438.72	0.057877	0.08736236	6.772	72.590
114	111.89	0.294882	91.28	0.26388	34.17	0.08314	34.61	0.12259	38.48	0.00246	348989.117	0.010656	0.11026132	3.234	6.009
115	100.6	0.265128	97.53	0.28194	33.02	0.08034	33.44	0.11844	94.29	0.00602	323976.324	0.009893	0.29103979	3.200	14.228
116	62.74	0.165349	64.71	0.18707	55.47	0.13497	56.18	0.19899	99.39	0.00634	225202.953	0.006876	0.44133524	4.376	25.196
117	66.51	0.175285	68.6	0.19831	58.81	0.14309	59.56	0.21096	118.45	0.00756	268325.683	0.008193	0.44144116	4.559	31.834
118	137.96	0.363588	114.76	0.33175	126.89	0.30874	128.16	0.45394	60.96	0.00389	2008959.23	0.061343	0.03034407	8.174	35.253
119	104.37	0.275063	104.37	0.30172	120.33	0.29278	121.35	0.42982	200.08	0.01277	1310766.35	0.040024	0.15264353	7.821	109.558
120	34.79	0.091688	34.8	0.1006	56.33	0.13706	56.98	0.20182	15.32	0.00098	68198.2804	0.002082	0.2246391	4.419	3.939
121	177.34	0.467373	91.3	0.26393	107.27	0.261	108.04	0.38267	116.07	0.00741	1736823.8	0.053033	0.06682889	7.126	56.585
122	97.73	0.257564	100.8	0.2914	86.42	0.21027	87.5	0.30992	375.75	0.02398	851339.321	0.025995	0.44136338	6.036	148.356
123	32.83	0.086522	32.83	0.09491	53.15	0.12932	53.82	0.19063	12.87	0.00082	57285.543	0.001749	0.22466401	4.233	3.126
124	167.09	0.440359	86.02	0.24867	101.07	0.24592	102.33	0.36245	97.09	0.0062	1452687.38	0.044357	0.06683475	6.333	44.831
125	53.7	0.141524	48.42	0.13997	25.4	0.0618	25.73	0.09113	22.41	0.00143	66043.9116	0.002017	0.3393197	2.76	8.56
126	45.96	0.121126	47.41	0.13705	40.64	0.09888	41.16	0.14579	39.08	0.00249	88553.0807	0.002704	0.44131723	3.580	7.258
127	82.44	0.217268	86.25	0.24934	84.25	0.20499	85.21	0.30181	301.8	0.01926	599055.413	0.018292	0.50379313	5.902	116.040
128	131.83	0.347433	87	0.2515	57.7	0.14039	58.37	0.20674	285.61	0.01823	661773.417	0.020207	0.43158276	4.496	75.225
129	52.75	0.139021	55.98	0.16183	108.8	0.26473	110.14	0.39011	31.55	0.00201	321280.416	0.00981	0.09820082	4.303	25.700
130	222	0.585073	81.46	0.23549	41.47	0.1009	41.95	0.14858	322.02	0.02055	749948.456	0.022899	0.42938951	3.635	60.956

0.51438	0.51012921	0.85982469	0.8685667	0.86857	0.77998596	0.77999	0.74012576	0.740126	0.00713651

Appendix 5

RM BUILD TIME AND PART COST MODELS USED BY WILSON (2006)

SPECIFIC RM BUILD TIME AND PART COST MODELS USED BY WILSON (2006)

Machine parameters:

L_vat	length of RP vat (x-direction) (mm)
H_vat	height of RP vat (z-direction) (mm)
W_vat	width of RP vat (y-direction) (mm)
ul	useful life of machine (yrs)

Scan profile parameters:

N_{scan}	number of times the given surface is scanned (drawn) for parts
$N_{scansupp}$	number of time the given surface is scanned (drawn) for supports
$supp\_factor$	factor used to account for inclusion of supports (%)
z_{supp}	minimum height of supports (mm)

Material Characteristics (coupled with machine in this project)

$dens$	material density (g/cm^3)
$MatC$	material cost per mass (\$/kg)

Material Deposition parameters:

D_{scan}	scan (draw) diameter (length)
$hatch$	percentage overlap of scans (%)
V_{jump}	jump velocity (mm/s)
V_{scan}	scan (draw) velocity (mm/s)
t_{layer}	layer thickness (mm)

Machine Time parameters:

$t_{preproc}$	time for preprocessing operations by the technician (hrs)
$t_{prostproc}$	time for postprocessing operations by the technician (hrs)
t_{draw_delay}	delay after draw, but before the stage moves
t_{stg_down}	time for stage to move down
t_{stg_delay}	delay time between stage movements
t_{stg_up}	time for stage to move up
t_{sweep}	time for material sweep
t_{swp_delay}	delay between material sweep and draw
t_{draw}	total time for scanning (drawing) part (s)
$t_{startup}$	machine warmup/setup time (s)
t_{sweep}	time for material deposition sweep (s)
t_{delay}	total time between scans (s)

Cost parameters:

$Mach\_rate$	cost of operating the machine per hour ($/hr)
$MachC$	cost of machine ($)
$MaintC$	yearly maintenance cost per machine ($)
$tech\_rate$	technician rate per hour ($/hr)

Appendix 6

Costing spreadsheets used for RM cost estimation

Costing spreadsheet for SLS DTM vanguard machine

Indirect costs

Production overhead	**€**	
Yearly rent rate (per m2)	130.50	
Building area (m2)	246.50	
Energy consumption/h	1.50	
Administration overhead	**€**	
Hardware purchase	2175.00	
Software purchase	2175.00	
Hardware cost/year*	435.00	
Software cost/year*	435.00	
Consumables per year	1450.00	
Production labour	**€**	
Technician annual salary + employer contributions	25450.00	(+ 22%)
Machine costs	**€**	
Machine & breakout station purchase	375000.00	
Purchase cost/year*	37500.00	
Maintenance/year	22500.00	
Software purchase	7250.00	
Hardware purchase	4350.00	
Software cost/year*	1450.00	
Cost of software upgrades/year	1450.00	
Hardware cost/year*	870.00	
Depreciation period for computer hardware	5.00	
Machine depreciation	10.00	
Uptime (%)		57.00

TOTALES			
Production labour/machine hour		6.2098	
Machine costs		12.75	
Production overhead		5.329553571	
Administrative overhead		0.464631899	
		24.75798547	
TOTAL BUIDTIME		45	
MATERIAL COST		54	/KG
		d	
Vp Part volume		19634	mm3
np total No of parts		1	
VB volume of the build		**19,634.00**	
Material density	ρ	0.000000475	kgr/mm3
mB		**0.00932615**	
PR		0.000424611	
Vbdes			
build bed		46,240,000.00	
Material used (MB)		0.01	
Alpha porcentaje desuso		0	
WB wasted material		0	
kilos de residuo		0	
Cost(mB) =		0.50	
Cost(tB) =		1114.109346	
		1114.613	

Costing spreadsheet for SLM concept Laser M1

Indirect costs

Production overhead	**€**	
Yearly rent rate (per m2)	130.50	
Building area (m2)	246.50	
Energy consumption/h	**3.45**	
Administration overhead	**€**	
Hardware purchase	2175.00	
Software purchase	2175.00	
Hardware cost/year*	435.00	
Software cost/year*	435.00	
Consumables per year	1450.00	
Production labour	**€**	
Technician annual salary + employer contributions	25450.00	(+ 22%)
Machine costs	**€**	
cost of filter change	**0.08**	
paper filter	**0.08**	
Inert gas	0.20	
Machine & breakout station purchase	359000.00	
Purchase cost/year*	44875.00	
Maintenance/year	9959.00	
Software purchase	**3141.00**	annual
Hardware purchase	0.00	interest
Software cost/year*	0.00	
Cost of software upgrades/year	0.00	
Hardware cost/year*	0.00	
Depreciation period for computer hardware	5.00	
Machine depreciation	8.00	
Uptime (%)	57.00	

TOTALES		
Production labour/machine hour	6.2098	
Machine costs	11.33	
Production overhead	7.279553571	
Administrative overhead	0.464631899	
	25.28078547	
TOTAL BUIDTIME	11	
MATERIAL COST	**245**	/KG
Vp Part volume	89000	mm3
np total No of parts	100	
VB volume of the build	**8,900,000.00**	
Material density ρ	**0.0000082**	kgr/mm3
mB	**72.98**	
PR	0.356	
Vbdes **build bed**	**25,000,000.00**	
Material used (MB)	72.98	
Alpha porcentaje desuso	0	
WB wasted material	0	
kilos de residuo	0	
Cost(mB) =Direct costs	17,880.10	
Cost(tB) = Indirect Costs	278.0886402	
TOTAL COST	**181.582**	

Costing spreadsheet for EOSINT M270

Indirect costs

Production overhead	**€**	
Yearly rent rate (per m2)	130.50	
Building area (m2)	246.50	
Energy consumption/h	**2.53**	
Administration overhead	**€**	
Hardware purchase	2175.00	
Software purchase	2175.00	
Hardware cost/year*	435.00	
Software cost/year*	435.00	
Consumables per year	1450.00	
Production labour	**€**	
Technician annual salary + employer contributions	25450.00	(+ 22%)
Machine costs	**€**	
cost of filter change	**0.08**	
different filters	**1.24**	
Inert gas	0.00	
Machine & breakout station purchase	540000.00	
Purchase cost/year*	67500.00	
Maintenance/year	25000.00	
Software purchase	**4725.00**	
Hardware purchase	0.00	
Software cost/year*	0.00	
Cost of software upgrades/year	0.00	
Hardware cost/year*	0.00	
Laser	**3.60**	
Depreciation period for computer hardware	5.00	
Machine depreciation	8.00	
Uptime (%)	57.00	

TOTALES		
Production labour/machine hour		6.2098
Machine costs		23.42
Production overhead		6.359553571
Administrative overhead		0.464631899
		36.45398547
TOTAL BUIDTIME		11
MATERIAL COST		**235**
Vp Part volume		89000
np total No of parts		5
VB volume of the build		**445,000.00**
Material density	ρ	**0.0000082**
mB		**3.649**
PR		0.033116279
Vbdes		
build bed		**13,437,500.00**
Material used (MB)		3.65
Alpha porcentaje desuso		0
WB wasted material		0
kilos de residuo		0
Cost(mB) =		857.52
Cost(tB) =		400.9938402
		251.702

Costing spreadsheet for MCP SLM Realizer 250

Indirect costs

Production overhead	**€**	
Yearly rent rate (per m2)	130.50	
Building area (m2)	246.50	
Energy consumption/h	**1.61**	
Administration overhead	**€**	
Hardware purchase	2175.00	
Software purchase	2175.00	
Hardware cost/year*	435.00	
Software cost/year*	435.00	
Consumables per year	1450.00	
Production labour	**€**	
Technician annual salary + employer con	25450.00	(+ 22%)
Machine costs	**€**	
cost of filter change	**0.08**	
different filters	**1.24**	
Inert gas	0.03	
Machine & breakout station purchase	409000.00	
Purchase cost/year*	51125.00	
Maintenance/year	15000.00	
Software purchase	**3579.00**	←
Hardware purchase	0.00	
Software cost/year*	0.00	
Cost of software upgrades/year	0.00	
Hardware cost/year*	0.00	
Laser	**2.50**	
Depreciation period for computer hardwa	5.00	
Machine depreciation	8.00	
Uptime (%)	57.00	

TOTALES			
Production labour/machine hour		6.2098	
Machine costs		17.08	
Production overhead		5.439553571	
Administrative overhead		0.464631899	
		29.18898547	
TOTAL BUIDTIME		11	
MATERIAL COST		**235**	/KG
Vp Part volume		89000	mm3
np total No of parts		1	
VB volume of the build		**89,000.00**	
Material density	ρ	**0.0000082**	kgr/mm3
mB		**0.7298**	
PR		0.005696	
Vbdes			
build bed		**15,625,000.00**	
Material used (MB)		0.73	
Alpha porcentaje desuso		0	
WB wasted material		0	
kilos de residuo		0	
Cost(mB) =		171.50	
Cost(tB) =		321.0788402	
		492.582	

Appendix 8

Sample materials database

Máquina	**Nombre/ fabricante**	**Caracteristicas**	**Coste (Dlls/ kg)**	**Wear resistance**	**Corrosion**	**Absorptivity**	**Tensile strength MPa**	**Tensile modulus MPa**
Z printer 310, Z-406, Z-810	Z CORP ZP14	polvo tipo escayola infiltrado cons infiltrante curable por calor	41.25	Low	Low	Low		12.9
Z printer 310, Z-406, Z-810	ZCORP ZP100	polvo tipo escayola infiltrado con infiltrante curable por calor	45	Low	Low	Low		11.7
Z-406, Z-810	ZCAST	mezcla de cerámica y polvo de escayola	56	Low	Low	Low		
Thermojet	MJM-3D Systems Thermojet 88	cera orgánica, cremosa, blancausada para modelos para IC. Colores negro, blanco y gris	218	Low	Low	Low		
Thermojet	MJM-3D Systems Thermojet 2000	cera orgánica, opaca; produce partes durables con buenos acabados	218	Low	Low	Low		
Invision3D	MJM-3D Systems VisiJet100	fotopolimero acrilico. Blanco, gris, rojo o negro. Partes durables con buen detalle	211	Low	Low	Low		24
Invision3D	MJM-3D Systems VisiJet HR-M100	fotopolimero acrilico. Blanco, gris, rojo o negro. Partes durables con buen detalle	234	Low	Low	Low		24
EOSINT M 270	EOS titanium CP2	fine-grained Ti commercially pure grade 2 powder. especially suitable for biomedical implants	254	High	High	High		
EOSINT M 250Xt	EOS Direct Steel 20	fine-grained steel-based metal powder. heavy-duty injection molds, direct manufacture of metal parts	254	High	High	High	580	
EOSINT M 250Xt, 270	EOS Direct Metal 20	fine-grained bronze-based metal powder injection molds and inserts for molding a few thousand parts, direct manufacture of metal parts	254	High	High	High	400	
EOSINT M 250Xt, 270	EOS Direct steel H20	fine-grained alloy steel powder injection molds with properties similar to those made of tool steels	254	High	High	High	1100	
Prometal r10	Stain less steel3:316 + Br		254	Low	High	Average	406	148000
Prometal r10	Stain less steel4:420 + Br		254	Low	High	Average	682	147000
Prometal r10	Stain less steel4H:420 + Br		254	Low	High	Average	765	151000
SLA	3D Systems AccuDur 100	resinas epox	175	High	High	High	50	2.28
SLA	3D Systems Accura SI 10	alte resistencia en verde, buena resistencia a la humedad, ideal para partes Quickcas, claridad optica y paredes finas	175	High	High	High	64.5	3203.5
SLA	Accura SI 20	material blanco, durable, ideal para snap fits, RTV y aplicaciones de moldeo	175	High	High	High	29	1230.5

SLA	3D Systems Accura SI 40	resinas epoxy fotopolimerizables. Fuerte, material de altas temperaturas, no quebradizo	175	High	High	High	61.85	3013
SLA	Accura Bluestone	material nano-composite, dureza excepcional, resistencia térmica y bajo, bajo nivel de contracción	175	High	High	High	67	9650
SLA	Accura Si 45HC	alta resistencia en verde, buena resistencia la humedad, velocidad de fabricación casi el doble que otras resinas	175	High	High	High	60	2860
SLA	Accura SI 50	material durable, natural o gris, ideal para snap fits y aplicaciones de moldeo de silicona	175	High	High	High	49	2585
SLA	Accura Amethyst	púrpura, capacidad de detalle y calidad de pieza superior, buena combinación de velocidad y calidad	175	High	High	High	30	3755
SLA	Accura SI 30	rápido, versatil, buena commbinacion de velocidad y durabilidad	175	High	High	High	30.25	1230.5
EOSINT M 270	EOS Stainless steel 17-4	fine-grained 17-4PH (1.4542) stainless steel powder. functional prototypes, small series production, individualized products etc. with high toughness and ductility	175	Average	Average	Average	900	
EOSINT M 270	EOS Cobalt chrome	fine-grained CoCrMobased superalloy powder especially suitable for biomedical implants and parts requiring high mechanical properties in elevated temperatures	175	Average	Average	Average	1400	
EOSINT M 270	EOS Titanum Ti64	fine-grained Ti6Al4V powder especially suitable for biomedical implants and parts requiring high strength to weight ratio	175	Average	Average	Average	1200	
DMLS	LaserForm ST-200	polymer-coated stainless steel powder. tooling material; provides performance similar to P20 steel	79	Average	Average	Average	435	
DMLS	LaserForm A6	polymercoated A6 steel and tungstencarbide powders. increasedhardness tooling material; similar to tool steel	149	Average	Average	Average	610	
EBM	ARCAM	ASTM F75 CoCr Alloy	340	High	High	High	960	
EBM	ARCAM	Ti6Al4V Titanium Alloy	400	High	High	High	850	120000
FDM	ABS P400	God chemical and thermal resistance. Finns in several colours.	150	High	High	High	34.5	2495
FDM	ABSi P500	For medical applications, can sterilised.	145	High	High	High	37.2	1963

FDM	ICW06 wax	For wax models for investment casting.	1544	High	High	High	3.5	275
Dimension Maxum, Titan TI, Vantage, SE, Vantage S, Vantage (when configured with ABS) Prodigy Plus	Stratasys ABS	durable, fuerte, buenas propiedades termicas y quimicas. Viene en varios colores	250	High	High	High	34.45	2495
Dimension Maxum, Titan TI, Vantage, SE, Vantage S, Vantage (when configured with ABS) Prodigy Plus	Stratasys ABSi	durable, fuerte, buenas propiedades termicas y quimicas. Viene en varios colores	250	High	Low	Average	37.21	1963
FDM-2000, FDM 3000	Stratasys ICW06 wax	cera para IC. Se quema mediante procedimientos convencionales	250	High	Low	Average	3.5	275
FDM-2000, FDM 3000	Stratasys Elastomer E20	material resistente y flexble ideal para sellar, juntas, empaques, etc	320	Low	Low	Average	64	69
Titan TI, Vantage S, Vantage SE, Vantage i	Stratasys Plicarbonato	termoplastico rigido, usualmente usado para fabricación	261	Low	Low	Low	63	2380
Titan TI	Stratasys Polyphenysulfona	termoplastico muy rigido usado para fabricación	450	Low	Average	Low	69	2312
Titan TI, Vantage S, VantageSE	Stratasys PC-ABS	esta mezcla combina las mejores propiedades de ambos materiales	261	Low	Average	Low	34.8	1827
FDM-2000/ FDM-3000/ FDM-8000/ Prodigy Plus/Quantum /Maxum/Titan/ Dimension	Sibco ABS multipurpose	durable, fuerte, buenas propiedades térmicas y químicas, viene en colores	80	Average	Average	High	27.25	1600
Objet	Full cure 720	acrylate photopolimer resin. Good impact strenght and flexural modulus with opaque colors	225	Low	Low	Low	60.3	2870
Objet	Vero white	acrylate photopolimer resin. Good impact strenght and flexural modulus with opaque colors	225	Low	Low	Low	49.8	2495
Objet	Vero blue	acrylate photopolimer resin. Good impact strenght and flexural modulus with opaque colors	225	Low	Low	Low	55.1	2740
SLA	Ciba (for SLA)		199	High	High	High		
SLA	SL 5510		199	High	High	High	77	3300
SLA	SL 5410		199	High	High	High	72	3100
SLA	Du Pont (for SLA)		199	High	High	High		
SLA	Somos 2100		199	High	High	High	9	80
SLA	Somos 8120	tiene propiedades similares al polietileno	230	High	High	High	25	585
SLA	Somos 7100		230	High	High	High	66	2324

SLA	Somos 6110		230	High	High	High	69	2800
SLA	SL7540	Analizada por Hague en su isotropía e impacto	230	High	High	High		
SLA-190	Vantico SL-5170	Universal material, epoxy. Best for snap functions.	230	High	High	High	59.5	2450
SLA	Vantico SL-5210	Extra temperature and water-resistant.	210	Average	Average	Average	15	1455
SLA	Vantico SL-5220	Universal material, epoxy. Better accuracy, shorter build times.	210	Average	Average	Average	62	2703
SLA	Vantico SL-5240	Have properties similar to thermo plastics.	210	Average	Average	Average	37	236
SLA	Somos 6110	Universal material, epoxy. Shrink less.	210	Average	Average	Average	69	2800
SLA	Somos 7110	Temperature and moisture resistant epoxy material. Fast.	225	Average	Average	Average	56	2117
SLA	somos 10110 waterClear	resina de proposito general con propiedades promedio. Produce partes claras	225	Average	Average	Average	43.4	2040
SLA	DSM Somos 14120	buena presición, resiste bien la suciedad, emula al ABS puede usarse para snapfits	220	Average	Average	Average	46	2460
SLA	DSM Somos 12120		220	Average	Average	Average	70.2	3520
SLA	DSM SOMOS 11120	Emula al ABS, usado para Investment casting, patterns y tooling	220	Average	Average	Average	50	
SLA	DSM SOMOS 10120	Emula al ABS, usado para Investment casting, patterns y tooling	220	Average	Average	Average	35	1960
SLA	DSM SOMOS 9120	Se comporta como el PP, alta enlongación	220	Average	Average	Average	31	1344.5
SLA	DSM somos ProTool 20L	Buena presición, resistencia a la temparatura, y alta dureza (stiffnes)	220	Average	Average	Average	75.5	10655
SLA	DSM somos Nanoform 15120	Buena resistencia altas temperaturas	220	Average	Average	Average	48	5000
SLA	somos 9110	resina robusta para piezas funcionales	225	Low	Low	Low	17	318
SLA	Somos 8110	Epoxy. Give more flexible details.	225	Low	Low	Low		
SLA	RPCure 100 HC	Universal material. High resolution, smooth surfaces and water-resistant.	220	Low	Low	Low	67	3210
SLA	RPCure 200 HC	Good impact strength, water resistant, fast.	220	Low	Low	Low	50	2000
SLA	RPCure 300 HC	Good temperature resistance; smooth surfaces and good mechanical properties.	220	Low	Low	Low	67	3000
SLA	RPCure 400 HC	Resistant to heat.	220	Low	Low	Low	39	2200
SLA	RPCure 550 HC	For medical applications. Can be sterilised.	220	Low	Low	Low	35	1300
SLA	RPCure 600 HC	Elastic, flexible, durable.	220	Low	Low	Low	44	1850
SLA-250	Vantico Stereocol H-C 9100R	Acrylic material for medical applications. Can be sterilised in autoclave.	220	Low	Low	Low	50	1389
SLA	Vantico Stereocol A-C 9200R	Acrylic material for medical applications. Can be sterilised in autoclave.	220	Low	Low	Low	45	1315
SLA-500	Vantico SL-5180	Universal material, Epoxy.	220	Low	Average	Average	46.5	2090
SLA-500	Vantico SL-5410	Universal material, Epoxy. Better accuracy, shorter build time.	220	Low	Average	Average	72	3095

SLA-500	Vantico SL-5430	Heat and water resistant material.	220	Low	Average	Average	46.5	503.5
SLA-500	Somos 6100	Universal material, Epoxy. Shrinks less.	220	Low	Average	Average	54	2690
SLA-500	Somos 7100	Temperature and water resistant Epoxy material. Fast.	220	Low	Average	Average	59	2282
SLA-500	somos 1110 waterShed	durable, fuerte, semitransparent, resina resistente al agua	235	Low	Average	Average	48.3	2.64
SLA-500	somos proto Therm 12110	fuerte, tolera altas temperaturas, resistente al agua, partes color cereza	240	Low	Average	Average	70.2	3520
SLA-500	Somos 8100	Epoxy. Gives flexible details.	220	Low	Average	Average	26	508
SLA-500	Somos 9100	Durable material for functional details.	220	Low	Average	Average	29.5	1278.5
SLA-500	Vantico Stereocol A-C 9200R	Acrylic material For medical applications. Can be sterilised in autoclave.	220	Low	Low	Low	45	1315
SLA-500	RPCure 100 AR	Universal material. High resolution, smooth surfaces and water-resistant.	220	Low	Low	Low	75	3020
SLA-500	RPCure 200 AR	Good impact strength, Water resistant, fast.	220	Low	Low	Low	50	2000
SLA-500	RPCure 300 AR	Good temperature resistance; smooth surfaces and good mechanical properties.	220	Low	Low	Low	60	3000
SLA-500	RPCure 400 AR	Heat resistant.	220	Average	Average	Average	39	1900
SLA-500	RPCure 600 AR	Elastic, flexible, durable.	220	Average	Average	Average	50	1825
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-5195	Universal material, Epoxy. Low viscosity.	225	Average	Average	Average	46.5	2090
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-5190	resinas epox	225	Average	Average	Average	56	2200
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-5510	Universal material, Epoxy. Resistant for moisture.	225	Average	Average	Average	77	3296
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-5520	Special material, Epoxy. Strong and flexible.	225	High	Average	Average	26.3	1206.5
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-5530H	Special material For higher temperatures. Epoxy.	225	High	Average	Average	58.5	3014.5
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-7510	Fast universal material. Resistant to moisture.	225	High	Average	Average	50.5	2420
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-7520	Universal material.	225	High	Average	Average	63.5	66
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL-7540	Have properties similar to thermo plastics.	225	Average	Average	Average	37.5	197
SLA-350 SLA-3500 SLA-5000 SLA-7000	Vantico SL7560	Simula propiedades del ABS de SL	225	Average	Average	Average		
SLA-350 SLA-3500 SLA-5000 SLA-7000	Somos 6120	Universal material, Epoxy. Shrinks less.	225	Average	Average	Average	43	2200

SLA-350 SLA-3500 SLA-5000 SLA-7000	Somos 7120	resinas epox	225	Average	Average	Average	58	2477
SLA-350 SLA-3500 SLA-5000 SLA-7000	somos 7620 Raven	resina de proposito general, produce partes oscuras	225	Average	Average	Average	57	2310
SLA-350 SLA-3500 SLA-5000 SLA-7000	somos 10120 Water Clear	proposito general, produce partes claras	225	Low	Low	Low	26	1710
SLA-350 SLA-3500 SLA-5000 SLA-7000	somos 11120 WaterShed	durable, fuerte, semitransparent, resina resistente al agua	235	Low	Low	Low	50.35	2765
SLA-350 SLA-3500 SLA-5000 SLA-7000	Somos 8120	Epoxy. Gives more flexible details.	225	Low	Low	Low	25.5	587.5
SLA-350 SLA-3500 SLA-5000 SLA-7000	Somos 9120	resinas epox	225	Low	Low	Low	36.5	1248
SLA-350 SLA-3500 SLA-5000 SLA-7000	RPCure 100 ND	Universal material. High resolution, smooth surfaces and water-resistant.	210	Low	Low	Low	75	3000
SLA-350 SLA-3500 SLA-5000 SLA-7000	RPCure 200 ND	Good impact strength, water resistant, fast.	225	Low	Average	Low	50	2000
SLA-350 SLA-3500 SLA-5000 SLA-7000	RPCure 300 ND	Good temperature resistance; smooth surfaces and good mechanical properties.	214	Low	Average	Low	60	3000
SLA-350 SLA-3500 SLA-5000 SLA-7000	RPCure 400 ND	Heat resistant.	200	High	High	High	39	1900
SLM	Stainless Stell 1.4404	Material	250	High	High	High	500	
SLM	tool steel 1,2343		289	High	High	High	810	
SLM	TiAL6V4		300	High	High	High	1300	
SLM	Steel 17-4	provided by Layerwise	250	High	High	High	1050	
SLM	Hardenable Stainless Steel 15-5	provided by Layerwise	225	High	High	High	1200	
SLS	PA12		90				50	1500
SLS	PA11		100	High	High	High	56	1200
SLS	Windform FX	Poliamide based, color white apt for flexible components, functional parts, clips and snapfits. Suited for aerospace and motor applications	112	High	High	High	48.96	1357
Fabricante crdm	Windform XT	Carbon filled, designed for F1, aerospace & wind tunnel applications	120	High	High	High	77.85	7320.8
Sinterstation and Vanguard	Duraform PA	blanco. Polyamide. Powder. good thermal stability and chemical resistance	132	High	High	High	44	1600
SLS	Duraform GF	color blanquisco. glass-filled polyamide powder. high-durability material; good thermal stability and chemical resistance	88	High	High	High	38.1	5910

SLS	DuraForm AF	polyamidealuminum powder. cast aluminum look with excellent surface finish, detail, and wear resistance	100	High	High	High	33	
SLS	CastForm	polystyrene powder. performs almost identically to foundry wax for shell investment casting	132	High	High	High	2.8	
Sinterstation® Pro and Sinterstation HiQ™ series SLS	Duraform Ex	Similar to injected PP and impact resistance like ABS	79	High	High	High	42.5	1517
SLS	DuraForm Flex	elastomeric plastic powder. rubber-like performance to simulate gaskets, hoses, seals; can be colored or pressure-sealed with infiltrants	79	High	High	High	10.8	
EOSint P	PA 2200	polyamide powder. Good thermal stability and chemical resistance	79	High	High	High	45	
EOSint P	PA 3200 GF	glass-filled polyamide powder. highdurability material; good thermal stability and chemical resistance	64	High	High	High	48	
SLS	Nylon PA 6		54	High	High	High	72	1900
EOSint P	Somos 201	elastomeric polymer powder. highly flexible with rubber-like properties	132	High	High	High		
EOSint P	PrimeCast 100	polystyrene powder. suitable for building investmentcasting patterns	99	High	High	High	3.35	
EOSint S	Quartz 4.2/5.7	phenolic resincoated sand. sand-casting patterns and cores	2.2	High	High	High		
EOSint P	Alumide	30%- aluminumfilled polyamide. stiff, durable parts with metallic appearance	68	Average	Average	Average	45	
SLS	Alumide	color plateado	220	Average	Average	Average	46	3800

Elongation at break %	Impact strength unnotched Kj/mm	Ball thrust hardness Shore N/mm	Flexural Modulus (MPa)	Density	Heat deflection Temperature oC	Melting point	Critical	Sanitary	Fire	Electrical	Material
3500		12.5	71	3500			0	0	0	0	4
4023		11.105	77	4023			0	0	0	0	4
							0	0	0	0	4
							0	0	0	0	4
							0	0	0	0	4
	15.6	13.3		775			0	0	0	0	4
	15.6	13.3		775			0	0	0	0	4
30							1	1	1	1	1
		30.2	130000	7.6			1	0	1	1	1
		20	80000	7.6			1	0	1	1	1
4		53.85	180000	7.8			1	0	1	1	1
		60					0	0	1	1	1
		30					0	0	1	1	1
		35									
15	25.1	82					0	0	0	0	4
4.8	17.1	86			56		0	0	0	0	4
20.5	34.35	84			54		0	0	0	0	4

5.8	26.1	87			101.5		0	0	0	00	4
1.9	15	92			65		0	0	0	0	4
5.1	13	87			54.5		0	0	0	0	4
10.15	22.3	86			48		0	0	0	0	4
0.8	10.5	87			69.5		0	0	0	0	4
18	31.03	84			54		0	0	0	00	4
30		54	190000				1	0	1	1	1
10		57.5	210000	8.3			1	1	1	1	1
8		45.2	120000				1	0	1	1	1
50		79	68500	6.73			1	0	1	1	1
50		30	69000	7.8			1	1	1	1	1
		34					1	1	1	1	1
8		33					1	1	1	1	1
10	107	78					0	1	0	0	2
10	176	76					0	1	0	0	2

10	17	13					0	0	0	0	2
10	107	78	2495				1	0	0	0	2
10	176	76	1963				1	0	0	0	2
10	17	13	275				0	0	0	0	2
10	347	96	69				0	0	0	0	2
	754	54	2380		125		1	0	0	0	2
7.2	782	78.5	2312		207		0	0	0	0	2
4.3	123	52.2	1827		110		1	0	0	0	2
12.29		37.5	1600		240		0	0	0	0	2
20	39.6	83					0	0	0	0	2
20	37.5	83					0	0	0	0	2
20	42.5	83					0	0	0	0	2
							0	0	0	0	4
5.4	27	99					0	0	0	0	4
4.2	37	127					0	0	0	0	4
							0	0	0	0	4
47	90	124					0	0	0	0	4
24	53.5	26.5					0	0	0	0	4
5.25	32	105					0	0	0	0	4

10	27						0	0	0	0	4
	6.3						0	0	0	0	4
13	28.5	85					0	0	0	0	4
1.2	21	84					0	0	0	0	4
8.3	37	86					0	0	0	0	4
24	48	84					0	0	0	0	4
10	27	87					0	0	0	0	4
6.25	27.8	82		1.13	74		0	0	0	00	4
37	45	83		1.12	48.5		0	0	0	0	4
8			2250		53		0	0	0	0	4
4			3320		56.5		0	0	0	0	4
15			2205		50.2		0	0	0	0	4
23			2250		52.9		0	0	0	0	4
20			1382.5		56.5		0	0	0	0	4
1.25			9420		258		0	0	0	00	4
2.1			3630		269		0	0	0	0	4
27	86	77		1.13	62.5		0	0	0	0	4
				1.11	46.5		0	0	0	0	4
4	21	85					0	0	0	0	4
17		82					0	0	0	0	4
3	7	86					0	0	0	0	4
1.7	7.1	87					0	0	0	00	4
9	18	86					0	1	0	0	4
20	4	81					0	0	0	0	4
8		75					0	1	0	0	4
7		75					0	1	0	00	4
11.5	39.5	84					0	0	0	0	4
4.2	39	86					0	0	00	0	4

2	15	90					0	0	0	0	4
8.5	33.8	84.5					0	0	0	0	4
5.6	26.7	86					0	0	0	0	4
25	19.3			1.12	49.6		0	0	0	0	4
4	11.5	85.3			53.75		0	0	0	0	4
20.5	55	81					0	0	0	0	4
15.5	54	85					0	0	0	0	4
7		75					0	1	0	0	4
9	30	83					0	0	0	0	4
17		80					0	0	0	0	4
3.5	15	86					0	0	0	0	4
1.7	9	86					0	0	1	0	4
21.05	4.4	80					0	0	0	0	4
16	54	83					0	0	0	0	4
9	27	80					0	0	0	0	4
5.4	27	86					0	1	0	0	4
33	59	80					0	0	0	0	4
4.1	21	88					0	0	0	0	4
8.95	32	87					0	0	0	0	4
423.5	3.35	90					0	0	00	0	4
20	29.5	81					0	0	0	0	4
							0	0	0	0	4
4	32	88					0	0	0	0	4

4.5	27	88		1.12	83.5		0	0	0	0	4
97	24	80		1.12	50.15		0	0	0	00	4
32	48	81		1.12	46		0	0	0	0	4
15.5	25			1.12	50.15		0	0	0	0	4
24	55	76.5		1.12	61.5		0	0	0	0	4
8	53.5	81		1.12	55.5		0	0	0	0	4
9	30	82		1.12			0	0	0	0	4
17		80					0	0	1	00	4
3.5	12	86					0	0	0	0	4
1.7	8	87					0	0	1	0	4
12.5		36					1	1	1	1	1
2.5		31					1	1	1	1	1
1.5		55.6		4.4			1	4	1	1	1
				7.8			1	0	1	1	1
		45		7.75			1	0	1	1	1
15	21	90		0.95			0	0	0	0	2
50	30	75		1.04			0	0	0	0	2
43.9	31.72		952.2	1.027	47.1	190.7	0	0	0	0	2
2.6	32.4		6248.5	1.101	175.4	179.33	1	0	0	0	2
9	214		1442.5	0.78	86	184	0	0	0	0	2
2	96		4605	1.12	110	185	1	0	0	0	2

			4400	0.89			1	0	0	0	2
	11		1604	0.46			0	0	0	0	2
47	64	74	1310		188		1	0	0	0	2
		60	8.15	0.44		192	0	0	0	0	2
20	440	75	1700	0.44		176	0	0	0	0	2
6	213	80	3200	0.605		176	1	0	0	0	2
90	8.01		2000	1.12	66	220	1	0	0	0	2
120.5		74.5	16.4	0.58		156	0	0	0	0	2
0.4			1600	0.61		105	0	0	0	0	2
				4.95			0	0	0	0	2
3		76	3600			180	0	0	0	0	2
4			2900	1.35	177.1	172	0	0	0	0	2

Appendix 9

Comparison of previous Rapid Prototyping selectors

System/ Developer/year	Description	Advantages	Disadvantages
Rapid Prototyping Program (Santa Clara University) Hornberger, L.E; Hight, T; Lawrence, E /1993	Intended for academic purposes provides general RP process info and basic selection from the systems available until 1993	First of its kind to spread the knowledge of RP in academic field. Offers comparisons between processes for a number of factors(cost, tolerance,sizes, etc.)	Fails to combine its variables to find the "best" RP machine. Limited scope of processes.
Rapid Prototyping System Selector (Bremen Institute of Industrial Technology and Applied Work Science BIBA) Muller, H; Bauer, J; Klingenberf, H / 1995	Uses a relational database management system aimed at selecting the best techology for a given set of part features	Includes the combined selection of materials and machine for a prototype fabrication. Also studies process chains selection for investment	The techniques used and software are not currently available
Database of RP system capabilities (University of Nothingham) Campbell, M; Bernie, M /1996	determines RP system capabilities for individual part`s features to extrapolate them to any other component	Includes a materials databse related to each process capability to relate it to entry information.	It is based on previously developed RP benchmark parts to store individual features information and predict capabilities for future cases. It does not include cost and time estimation algoritms
RP Advisor (Arizona State University) Phillipson, D; Henderson, M / 1997	It has 2 functionalities:RP selection for machine purchase or for single part fabrication. Based on mathematical formulations takes into account a number of factors including cost, build time and Quality	Includes a build time estimator model for each process considering pre and post-processing times as a fraction of total build time. Useful to evaluate RP machine purchase	Lacks of a RP materials properties database. The data source of build time and cost calculation is not clear. - It handles only with quantitaive data input
Rapid Prototyping design advice system Bibb, R; Taha, Z, Brown, R; Wright, D /1999	One of the first systems to rely on expert system techniques. Presented as a rule-based software, it`s also one of the first ones to interact with CAD systems	Includes a subroutine to interpret 3D CAD models to feed the initial design requirements. It also takes into account Rapid Tooling technologies depending on the number of parts requiered.	There´s not a clear explanation on cost and build time models used. 3D model info extraction might be limited.
ACPIR: Knowledge based system for RP process selection (Ecole Centrale de Nantes, France) Bernard, A; Deglin, A; Ris, G / 1999	A knowledge based system for the selection of RP systems including CAD, reverse engineering and RT methods, from a set of initial factors (cost, quality, delay, aspect, material, etc)	Includes more technologies as primary, secondary and tertiary processes to arrive to the desired solution	In its intent to cover a wider range of technologies the system results are rather limited to a single process three without further analysis information
IRIS: Ruled Based expert system for RP system selection (Swinburne University of Technology, Australia) Masood, S.H; Soo, A / 2001	The system is based on a rule-based expert system including an extensive manufacturers databse from USA, Japan, Germany and Israel	Sets an interactive question-answer session with the user allowing four modes: quick selection, detailed selection, build technology or machine style	The system is inteded to provide the user with detailed technical info from single processes to make a desition, however it lacks of cost and builtime estimator for automatic comparison.
RP Selector (Helsinki University of Technology) Hannu Kaikonen / 2002	A simple JAVA program that runs in the web browser which trhough a series of questions and value rating presents one or more recomended technologies	One of the first web-based systems with simple straightforward logic. It also includes an option for importance ranking to rate the weight of each introduced factor	User interface is questionaire-type and the systems does not give an answer until all 12 questions and its scale factors are completed. No cost, build time and comparison alternatives given.
Decisión Support system for Rapid Prototyping process selection (Xiàn Jiaotong University, China) Lan, H; Ding Y; Hong J /2004	Probably the first system to integrate a Fuzzy synthetic evaluation in an expert syetm for process selection. Is divided in two parts: expert system selection, 2. model for alternatives ranking	Takes into account the inhenernt vagueness and uncertainty of qualitatyve descriptions of RP processes to integrate them in the final decisión	system for subjective data treatment causes that most of the input data is required in fuzzy intervals. No real or integer numbers are accepted and some technical and cost data that should be of the system´s domain, is asked to the user
RP Selector Industrial Research ar	Web based system for RP system selection focused on two main options: visualisation and functional prototypes	Web based platform that provides links to useful technical information such as product properties and functions and material data tables	Reduced scope of options which by asking 2 to 3 questions presents a wide non-rated scope of posibilities. No cost, time, or importance index is applied

Flexman. Rapid Manufacturing Selector ASERM Spanish Rapid Manufactuinn Association /2006	This is the only existing selection system that is named after the term RM instead of RP. It´s web based system which It also includes RT processes which cover with more detail	It also considers RT techniques as part of the alternatives besides other manufacturing techniques such as EDM, Laser cutting, Dieless forming, etc	Only few questions are made regarding additive methods, when the system detects the desired material or the number of parts is not suitable, it displays a Rapid Tooling query box, turning it into a Tooling questionaire

System/ Developer/year	User Inputs	Output provided	Internal logic
Rapid Prototyping Program (Santa Clara University) Hornberger, L.E; Hight, T; Lawrence, E /1993	NO user input is acepted, only pre-defines answers -The program queries for 4 individual selections: Appearance Smooth surface, rough surface, wooden or mould), Functionality, Geometry, Cost factors	A non-ranked list of suitable processes according to the selection.	Database and programing
Rapid Prototyping System Selector (Bremen Institute of Industrial Technology and Applied Work Science BIBA) Muller, H; Bauer, J; Klingenberf, H / 1995	-Surface -Acuracy -Material Material properties -Dimensions -Tool life (in case of tooling) -Lead time	A final score based on the fulfilment on input data	Uses the method of "Benefit Value Analysis" to evaluate the best selection. Makes use of Ms Acces relational data base capability.
Database of RP system capabilities (University of Nothingham) Campbell, M; Bernie, M /1996	-Maximum shape - Tolerances for each feature It departs from a number of part features (round boss, blind hole, tappered inside-outside diameters, square hole and boss, etc) to verify its manufacturability agains stored process data	Provides a ranking of the best combination process - material: An example of the evaluation is ``Frst place, 83% of requirement degree, for the machine ABC with material XYZ'' (MuÈller, 1996).	Use of Relational databases trhpugh ms Acces
RP Advisor (Arizona State University) Phillipson, D; Henderson, M / 1997	-Part´s maximum Widht, Lenght, Height -Dimensional accuracy:±0,02 , 0,03, 0,05 or another. -Surface finish: 500micro in, 32 micro in, 1 micro in, Other Machine selection by:Manufacturer, Tecnology, Company or all. -Time, Cost and Quality are entered as importance factors from 1 to 100 each -3 options: Simple, Medium, Complex (Its considered as an addtion of finest detail level and minimum wall thickness) -Plastic or metal parts	Provides a single reault of the most suitable process for a given entry. No machine info, nor technology ranking is given	Makes use of an agregate of normalized values for cost, build time and quality calculation trhough aritmetical formulation. The endresult is a non-dimensional rating for comparing the best options. It also uses Ms Acces
Rapid Prototyping design advice system Bibb, R; Taha, Z, Brown, R; Wright, D /1999	-Minimum wall thickness. -Maximum aspect ratio. -Accuracy -Number of parts required -Type of materisl -Parts end use	Displays a list of suitable methods and their relative merits besides aditional info.	Use of ruled based systems logic through IF-THEN-ELSE operators
ACPIR: Knowledge based system for RP process selection (Ecole Centrale de Nantes, France) Bernard, A; Deglin, A; Ris, G / 1999	1- Initial state of the part: type of model, aspect. 2- Parameters of delivery: desired quantity, delivery time. 3.Part parameters: lenght, width, height, exact volume, minimum thickness, value of smallest detail, minum blending radius, precision, surface quality, mono or multiple fabrication, part of a tool, topology of material	Shows a three structure with the recomended technologies in order of application	Developed on KADVISER from KADETECH. -Case-based reasoing (retrieval of previous case studies solutions). -botton-up generation of processes

IRIS: Ruled Based expert system for RP system selection (Swinburne University of Technology, Australia) Masood, S.H; Soo, A / 2001	* Price of the RP machine. * Dimensionalaccuracy along X–Y direction. * Dimensionalaccuracy along Z direction. * Surface finish on the built part. * Maximum dimensions of the part building envelope. * Range or type of available build materials. * Range of layer thickness for part building. * Speed of part building.	Prides a final screen with the a single recomended process and additional technical inforrmation	Developed within the Visual Basic module of the M4 expert system shell, based on 500 rule of the IF-THEN-ELSE type. The relation between valid inputs is controlled via SQL scripts
RP Selector (Helsinki University of Technology) Hannu Kaikonen / 2002	-Part accuracy -Layer thickness -Geometric features -material and application requirements. Four options are presented for each question	A list of the three best systems is displayed which satisfy input requirements	Database comparison and macthing, JAVA written web based program
Decisión Support system for Rapid Prototyping process selection (Xiàn Jiaotong University, China) Lan, H; Ding Y; Hong J /2004	-Dimensional accuracy -Surface roughness -lenght -Width -Heinght -Solid -Minimum wall thickness -Mechanocal behavour -Heast resistance -Use of the model -Master model -running cost -post-processing cost -material cost -equipment cost -scan speed -overhead time -post-processing time -prototypoe material -Number of parts	A single list with two or more suitable processes is shown. No additional technical info or comparison options are provided.	Makes use of the JESS 4.4 expert system shell using IF-THEN-ELSE type logic (126 rules) , besides mathematical model and fuzzy synthetic evaluation methods. (AHP methodology (Saaty, 1980)
RP Selector Industrial Research ar	-Part end use -Largest dimension -Number of parts -Level of material needed (near final, final properties, higher wear and mechanical properties)	Provides a box of posible solutions including for each process: presisio, complexity, delivery time, price, number or process steps	The logic is inverse in comparison with other systems, since the rankins of each technology are presented as final information. Criteria data used for selection is based on basic prcess capability: build size, material compatiblity, etc)
Flexman. Rapid Manufacturing Selector ASERM Spanish Rapid Manufactuinn Association /2006	-Maximum part dimensions -Type of material -Tolerances required -Finishing or color -Number of parts TOOLING querys:	Displays a box containing different alternatives and the level of fulfilment towards criteria such as time to market, cost and quality	Not available /not published

Curriculum breve. Dr Tahar Laoui

Tahar Laoui es Ingeniero en Metalurgia (1983) por la Universidad Politécnica Nacional de Argelia, Master en ciencias de Ingeniería de materiales por la Universidad de Washington (1986) Seattle, Estados Unidos y Doctor ingeniero en materiales y metalurgia (1990) por esta misma Universidad.

Historial de actividad

- 2008- actualmente King Fahd University of Petroleum and Minerals (Arabia Saudita). Departamento de Ingeniería Mecánica.
- 2001 – 2008: Senior Lecturer / Profesor asociado. University of Wolverhampton, School of Engineering & Built Environment. Reino Unido
- 1991-2001: Postdoctoral researcher/Senior Research Fellow / Lecturer.
- University of Leuven, Department of Metallurgy and Materials Engineering. Bélgica.
- Consultor de las Naciones Unidas para el programa PNUD-TOKTEN: 1997
- 1986 – 1990: Profesor asistente / Investigador asistente
- Universidad de Washington. Departamento de Ciencias de Materiales e Ingeniería. Seattle, EUA.

Áreas de interés:

- Nanotecnología: procesamiento de materiales avanzados / nano materiales y compuestos
- Estudio de materiales compuestos en cuanto a: estructura- propiedades-procesamiento
- Tecnologías de Rapid Prototyping & Rapid Manufacturing
- Tecnologías de caracterización mediante electro- microscopía (SEM & TEM)

Curriculum breve. Dr Alain Bernard

Alain Bernard es Ingeniero en producción (1982) por la École normale supérieure de Cachan, Francia. Y Doctor por la misma Institución (1989) con su Tesis sobre el tema: 3D feature-based manufacturing of forging dies.

Historial de actividad

- 2001 – actualmente: Ecole Centrale de nantes. Director de investigación: Ecole Centrale de Nantes
- 1996 – 2001: Profesor en el laboratorio CRAN. Research Centre for Automatic Control of Nancy, Francia
- 1990 – 1996: Profesor asistente Ecole Centrale Paris. Research laboratory on Mechanical Engineering and Logistics

Cargos adicionales

- 2000 – 2006 Miembro del comité científico del National Research Group (MACS: Modelling and Analysis of Complex Systems) dependiendo del Consejo Nacional de Investigación de Francia
- Fellow member of CIRP (International Academy of Production Engineering)
- Senior member of SME, SPIE, ASME y SMA.

Áreas de interés:

- Knowledge Based Engineering
- Ingeniería inversa, procesos para contextualización y digitalización
- Diseño de producto y fabricación
- Rapid Prototyping & Rapid Manufacturing

Curriculum breve. Dr Joaquim de Ciurana

Joaquim de Ciurana es Doctor Ingeniero Industrial (1998) por la Universidad Politécnica de Cataluña presentando la tesis titulada "Contribució a les bases conceptuals per la implantació de l'acotació funcional unidireccional en sistemes CAD". Actualmente es Catedrático de la Universidad de Gerona en el departamento de Ingeniería Mecánica y de la Construcción Industrial.

Publicaciones relacionadas con la Tesis:

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Curriculum breve. Dr Javier Muniozguren Colindres

Javier Muniozguren es Doctor Ingeniero Industrial y director del Departamento de Expresión Gráfica y Proyectos de Ingeniería de la Universidad del País Vasco. De igual forma es líder del Laboratorio de Diseño de producto (PDL) de la facultad de ingeniería de Bilbao.

Artículos de revistas de interés:

- Diseño de un nuevo proceso de modelizado digital de tablas de surf.
Rikardo Mínguez Gabiña, Javier Muniozguren Colindres
Fabrikart: arte, tecnología, industria, sociedad, ISSN 1578-5998, Nº. 6, 2006, pags. 160-168

- Arco de San Mamés
Javier Muniozguren Colindres, Isabel Larrakoetxea Madariaga
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- Ecodiseño de un producto y desarrollo sostenible
Javier Muniozguren Colindres, Rikardo Mínguez Gabiña
Fabrikart: arte, tecnología, industria, sociedad, ISSN 1578-5998, Nº. 5, 2005, pags. 40-53

- Determinación de volúmenes generados por la intersección de superficies cualesquiera
María Isabel Larracoechea Madariaga, C. Rebollar, Javier Muniozguren Colindres, M. Pinedo
VIII Congreso Internacional de Ingeniería Gráfica : actas, Vol. 2, 1996, ISBN 84-88942-73-7, pags. 499-506

Curriculum breve. Dr Joan Vivancos Calvet

Joan Vivancos Calvet es doctor ingeniero industrial y catedrático de la Universidad politécnica de Cataluña, en el departamento de Ingeniería mecánica. Actualmente forma parte del grupo de investigación TECNOFAB (Grupo de Investigación en Tecnologías de la Producción). A la fecha ha publicado múltiples artículos de revista, libros especializados y obras de referencia para cursos de ingeniería mecánica.

Articulos de revista de interés:

- Rojas, H. A. G.; Calvet, J. V.; Bubnovich, V. I.. (2008). A new analytical solution for prediction of forward tension in the drawing process. *Journal of materials processing technology* , 198 (1-3) : 93-98. ISSN: 0924-0136
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