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**RMADS: Development of a concurrent Rapid Manufacturing Advice System**

by

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*En realidad, sólo existe la dirección que tomamos...*  
(M. Benedetti)



## Abstract

The official date of birth of Rapid Manufacturing is usually located between 1988 when the American company 3D Systems introduced the first commercial Rapid Prototyping (RP) machine with the Stereolithography process, and 1992 when this machine was being acquired by engineering centres around the world, starting a new era of manufacturing.

Since then a number of relevant studies emerged regarding the so called “Solid Free Form fabrication” (SFFF). One of the classic reports that most experts in the field have referenced and whose illustrations and main content is still being used by researchers in the field is the ‘JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan’ published by the Society of Manufacturing Engineers (SME) in 1997. This report can be considered the most comprehensive and valuable sources of early information on additive methods. From this report to the present, many changes have occurred in the Rapid Prototyping field, for instance many of the emerging venture firms making introductions during the early stages such as: BPM, Soligen, Helisys, Teijin Seiki either have left the business or changed their strategy to operate as a service bureau. However since 1992 to the present, the launch of new RP/RM equipment and process improvements has been a non-stop.

It is hard to track the developments and state of the art of such a changing and dynamic area. From the beginning of this research in late 2004 until 2009 a number of shifts in the paradigm have occurred. While an important amount of research efforts remained focusing on prototyping, industry was moving towards ‘manufacturing’; while the topic of Rapid Prototyping was timidly included in engineering education curriculum, industry was creating Rapid Manufacturing associations and partnerships; while academia and industry were focused on finding industrial ‘niche applications’, young entrepreneurs worldwide were creating new business models based on the unusual capabilities of additive processes.

On a regional level the picture was not different. When Dr. Carles Riba, head of the CDEI centre of the Technical University of Catalonia came up with this project’s idea, the research focus was rather unclear. It took around one year of field research, consultation with experts, attendance to industrial events and visits to local machine-shops, and engineering centres to fine tune the research objectives. During this period also the Spanish Rapid Manufacturing Association was established, contributing to the clarification of the role of academia on a regional basis.

Rapid Manufacturing can be understood as a collection of manufacturing processes which are able to generate fully finished parts directly from a 3D model. This model can be either modelled in a CAD package or extracted by reverse engineering methods to obtain a solid geometry. Most RM methods are based on layer-wise deposition of material i.e. the final part is constructed by sections of material being joined by different enabling technologies, for instance: laser sintering, UV light curing, or powder bonding, between many others.

The material options are reduced as they normally include: polymers (ABS, PA, and PC), metals (stainless steel, aluminium, titanium and alloys), plaster type materials, wax and a wide range of photo-polymers. Lately the advantages of additive manufacturing are being explored by means of functionally graded materials and structurally charge formulations, however these findings have little commercial effect.

Only few RM technologies are capable of providing final mechanical properties nearly similar to conventional processes such as injection moulding, sand/ investment casting, etc. On a general basis the layered nature of Rapid manufactured parts present differences in the material's composition and behaviour. For instance, some RM parts exhibit anisotropic behaviour specially when built vertically, while other phenomena such as stair stepping or orange peel may be present due to build parameters calibration and orientation.

The adoption of RM as a conventional manufacturing route for automotive, aeronautical and medical industries is specially challenging and therefore has received special attention and interest from the RP/RM community, however for less demanding fields, the benefits of Rapid manufacturing regarding freedom of design and economic production of one-of or small series already comprise a competitive advantage. The awareness of these 'hidden' advantages however, remains slow, especially for SMEs on a regional level which tend to preserve their conventional manufacturing facilities and are not capable of making major investments.

Rapid Manufacturing equipment is not especially cheap, it is actually quite costly and the prices especially for metal-based processes and laser sintering equipment remain high, here is where specialized service bureaus show their advantages, nevertheless most of them have failed short to communicate potential users about the possibilities and advantages of RM.

The intention of this research is to go beyond currently available systems for the assessment and selection of Rapid Prototyping processes, hence introducing a new methodology devoted to 'Manufacturing' applications. Specifically the system would include a number of state of the art artificial Intelligence techniques to comprise a fully concurrent methodology, namely:

- Expert systems are included to aid in the decision making process with multiple alternatives. Expert systems typically use If-Then-Else or CASE structures so that the available options can be screened specially during the first selection stages.
- Fuzzy logic for decision making. Usually in manufacturing, linguistic terms or qualitative parameters are used to define states of properties. For instance it is common to find terms such as 'Good mechanical properties' or 'High absorptivity rates' therefore it is necessary to have a method to translate and manage such information. Fuzzy logic has been adopted as a means to translate qualitative terms to quantitative information.
- Multi-criteria decision making, aggregation and ranking. Different methods for selecting and ranking alternatives were tested which allows the integration of quantitative vectors with weighting factors that reflect the user preferences. For this purpose the method proposed by Lan et al. (2005) has been adopted as discussed in Chapter 5.
- Artificial Neural Networks (ANNs) are being applied for the modelling and simulation of a number of Rapid Manufacturing Methods. Selective Laser Sintering has been modelled using a back propagation algorithm ANN taking as a basis the information provided by the machine software. The ANN simulates a DTM Vanguard SLS machine available at Fundacio CIM-UPC, Barcelona, while the Selective Laser Melting has been modelled with the parameters and settings used by the Concept Laser M2 machine available at the Mechanical Engineering Lab of the Catholic University of Leuven, Belgium. The extracted models exhibit a build-time prediction error rate lower than 10%, which is a significant improvement compared to conventional parametric methods.
- Finally, relational databases have been applied for storing and handling materials information. These databases have been stored as Ms Access data which provides the ease to access, filter, screen and plot



the required information. This data can be automatically called and extracted by means of an ODBC call deployed within the Matlab environment.

In order to illustrate the functionality of the previous tools put together, a pilot application was designed in Matlab, making use of a number of specialized toolboxes namely: Fuzzy logic, Neural Network, Statistics, Plotting utilities, GUI builder, Database.

The result is a prototype system with a graphic user interface divided in three modules:

- General design requirements: which deals with those parameters usually defined in the product PDS, for instance: material type, tolerances, surface roughness, geometrical complexity, etc.
- Costing module: which makes use of parametric cost estimation and ANN-based models to perform the calculation of cost per part, and for low volumes
- Materials selection: Shows the iterative nature of materials selection through screening steps so that the range of suitable options is limited.

By illustrating a number of case studies from the machinery design and special mechanical parts, the usefulness of such a system is tested. In the final chapter some discussions are established on the suitability of Rapid Manufacturing for end use applications as well as the main constraints they might face. While the first module devoted to general design requirements performs a basic RM process screening, the other two modules have proved to be more restrictive. For instance, costing factors may show marked differences between metal and polymer based technologies, while materials factors tend to show functional properties regardless of economic factors.

The intention of such system is to provide a Knowledge Based Environment (KBE) for the selection of RM processes especially for non-experts and new-comers to the field of additive technologies.

Although the pilot application may lack an appropriate user interface for a more friendly use, the system is a first step towards a standardized system for the selection of manufacturing processes. It is the purpose of this work to present a feasible selection methodology on the one hand, and on the other hand a prototype application which may be used as educational tool for higher technical education. Although the aim is not the full migration to additive technologies (yet), a sufficient achievement for this project will be to make students and non experienced new-comers wonder: What happens if I do it the other way?

## Resum

La data oficial de l'aparició del 'Rapid Manufacturing' se situa entre 1988, any en què la companyia nord-americana 3D Systems introduïa el primer sistema comercial de Prototipat Ràpid (RP de l'anglès Rapid Prototyping) a través de la tecnologia de Estereolitografia, i 1992, quan les primeres màquines van començar a ser comercialitzades, sent adquirides per centres d'enginyeria a nivell mundial, iniciant així una nova era de la fabricació.

Des de llavors han sorgit un creixent nombre d'estudis i recerca relacionades amb l'anomenada 'Fabricació de Forma Lliure' (o SFFF de l'anglès Solid Free Form Fabrication). Un dels estudis clàssics que la majoria d'experts i investigadors han referenciat alguna vegada en els seus treballs és el titulat 'JTEC / WTEC Panel Report on Rapid Prototyping in Europe and Japan' publicat per l'Associació d'Enginyers de Fabricació de Estats Units (SME) el 1997, podent ser considerat com una de les fonts d'informació més completes i valuoses en el camp del Prototipat Ràpid de l'època. Des de llavors a l'actualitat s'han produït diversos canvis en l'escenari del RP, per exemple, algunes de les empreses pioneres en la introducció al mercat de tecnologies additives de fabricació com ara: BPM, Soligen, Helysis, TEIJIN Seiki han desaparegut o han donat un gir a la seva estratègia, per exemple, operant com un centre d'assessoria tecnològica. No obstant això des de 1992 a l'actualitat, el llançament de nous equips i tecnologies de RP o RM ha continuat de forma ininterrompuda.

És difícil fer un seguiment als desenvolupaments i l'estat de l'art d'una àrea tan dinàmica. Des de l'inici d'aquesta investigació doctoral el 2004, fins al 2009, s'han presentat alguns canvis en el paradigma de 'Rapid Manufacturing'. Mentre una quantitat important dels esforços de recerca fins a 2004 es concentraven a "prototipatge", la indústria es mobilitzava cap a la 'fabricació', mentre el tema de 'Prototipat Ràpid' a l'acadèmia era tímidament inclòs en el currículum d'estudis d'enginyeria, la indústria creava Associacions i consorcis de 'Fabricació Ràpida', mentre l'acadèmia i la indústria es concentraven a trobar aplicacions industrials especials (nínxols), joves emprenedors de tot el món creaven nous models de negoci i serveis basats en les inusuals capacitats dels processos additius.

A nivell local i regional l'escenari no era diferent. Quan el Dr Carles Riba, director del centre de Disseny d'Equip Industrials de la Universitat Politècnica de Catalunya, va proposar la idea d'aquesta recerca, l'objectiu final era més aviat difús. Va ser necessari al voltant d'un any d'investigació de camp, consultes i entrevistes amb experts, assistència a fires i esdeveniments industrials així com visites a tallers locals i centres d'enginyeria per afinar els objectius de la investigació. Durant aquest mateix període es va conformar l'Associació Espanyola de Rapid Manufacturing, contribuint a aclarir quins són els interessos de recerca i el rol de la recerca universitària en un context regional.

Rapid Manufacturing pot ser entès com una conjunt de processos de fabricació capaços de generar peces funcionals directament a partir d'un model en 3 dimensions. Aquesta peça pot ser ja sigui, modelada en un software CAD, o extreta mitjançant mètodes d'enginyeria inversa per a obtenir una geometria sòlida. La major part dels processos de RM estan basats en la deposició per capes de material, per exemple: sinteritzat làser, cura per llum ultraviolada, agents adhesius, entre d'altres. Les opcions de materials en l'actualitat són bastant reduïdes ja que inclouen: polímers (ABS, PA, Policarbonat, etc.) Metalls (acer inoxidable, alumini, titani i aliatges), materials similars a la escaiola, cera així com un ampli rang de fotopolímers. Recentment els avantatges de la fabricació additiva estan sent explorades mitjançant materials

avançats com: amb funcionalitat gradual i formulacions amb formulacions estructurals modificades, però aquests desenvolupaments han tingut a la data només un reduït efecte comercial.

De les tecnologies del Rapid Manufacturing actualment disponibles només unes poques són capaços de proporcionar propietats mecàniques similars a les de processos convencionals, com exemple: emmotllament d'injecció, bugada en sorra, micro fusió, etc. De forma general, la naturalesa additiva de les peces produïdes per Rapid Manufacturing provoca diferències en la composició i comportament del material. Per exemple, algunes peces fabricades per aquest mitjà presenten un comportament anís tròpic especialment quan es fabriquen amb una orientació vertical, mentre que altres fenòmens com el 'escalonat' o la 'pell de taronja' solen aparèixer a causa de diferències en els paràmetres de calibratge i orientació.

L'adopció de RM com una alternativa de fabricació per a sectors com el d'automoció, aeronàutica i medicina, és especialment complexa i al mateix temps d'un alt interès, per tant aquest sectors han rebut una atenció especial per part de la comunitat científica i industrial del RP i RM.

No obstant això, per a altres camps amb menors requeriments funcionals, els beneficis del Rapid Manufacturing sobretot referents a: llibertat de disseny i producció econòmica de sèries curtes o unitàries, actualment constitueix un avantatge competitiu. El reconeixement d'aquests avantatges 'ocultes' però, avança a ritme lent sobretot per a petites i mitjanes empreses a nivell local, que no compten amb la capacitat de realitzar altes inversions en materials i equips i per tant tracten de cenyir-se i optimitzar les prestacions dels seus equips actuals.

Els equips de RM no són especialment barats, de fet el seu preu és elevat especialment per a les tecnologies de processament de metalls equipades amb làser, així com per al sinteritzat làser de polímers. És aquí on els centres tecnològics i de serveis mostren la seva capacitat per oferir serveis especialitzats estalviant doncs els costos de propietat i manteniment d'aquesta classe d'equips als seus clients. No obstant això tant els centres de servei, prototipatge i centres tecnològics no han aconseguit comunicar de manera efectiva a un públic més ampli els avantatges de treballar amb Rapid Manufacturing.

La intenció d'aquest projecte de recerca és anar més enllà de l'aconseguit pels sistemes existents de selecció i comparació de processos de Prototipat Ràpid, mitjançant la introducció d'una nova metodologia que tingui com a únic fi la 'Fabricació Final' de components. El sistema desenvolupat incorpora algunes de les eines més recents del camp de Intel·ligència Artificial, de manera que sigui possible aconseguir una metodologia concurrent que inclogui:

- Sistemes experts, que s'executen durant el procés de presa de decisions amb alternatives múltiples. Els sistemes experts utilitzen típicament estructures del tipus: IF-THEN-ELSE o CASE, de manera que les opcions puguin ser 'cribrades' especialment durant les primeres etapes de la selecció.
- Lògica difusa per a la presa de decisions. Normalment en l'àmbit de la fabricació, alguns termes lingüístics o paràmetres de tipus qualitatiu són utilitzats per definir estats o propietats. Per exemple és comú trobar termes qualitius com ara: 'bones propietats mecàniques "o" alta taxa d'absorbència', en lloc de xifres i números puntuals. Per tant és necessari comptar amb un mètode per traduir i gestionar aquesta informació. La lògica difusa ha estat adoptada com a mitjà per traduir termes d'ordre qualitatiu a informació quantitativa de manera que a partir d'aquestes dades es pugui construir un sistema de classificació i rànquing de processos.
- Presa de decisions Multi-criteri, agrupació (sumatòria) i classificació. Durant la investigació es van provar diferents mètodes per a la classificació d'alternatives i selecció final a partir de vectors d'ordre

quantitatiu amb pesos ponderats. Per a aquesta finalitat es va adoptar la metodologia proposada per Lan et al. (2005) el qual es descriu en el capítol 5 d'aquest treball.

- Xarxes Neuronals Artificials. Aquestes han estat aplicades per a la modelització i simulació d'alguns processos de Fabricació Ràpida prèviament seleccionats. Per exemple, el procés de Sinteritzat Selectiu Làser es va aconseguir modelar utilitzant Xarxes Neuronals amb un algorisme de "backpropagation", prenent com a informació base, les dades proporcionades pel software propietari de l'equip. Aquesta xarxa neuronal simula una màquina de sinteritzat làser model DTM Vanguard, disponible a la FundacióCIM-UPC a Barcelona. D'altra banda el procés de Fusió selectiva per làser ha estat modelat també mitjançant Xarxes Neuronals a partir de l'equip Concep Laser M2, disponible al laboratori d'Enginyeria mecànica de la Universitat Catòlica de Lovaina, Bèlgica. Els models extrets d'aquestes simulacions mostren una estimació del temps total de fabricació menor al 10% la qual cosa representa una millora substancial respecte a mètodes d'estimació paramètrics.
- Finalment s'ha utilitzat la tècnica de bases de dades relacionals per a la gestió i emmagatzematge d'informació sobre materials. Aquestes bases de dades han estat creades en Ms Access, que proporciona la facilitat d'accés, filtrat, graficació i presentació de la informació requerida. Aquesta informació pot ser extreta automàticament mitjançant trucades ODBC, executades des de l'entorn Matlab.

Per a il·lustrar el funcionament de les eines descrites en una forma integrada, s'ha optat per desenvolupar una aplicació pilot en Matlab, utilitzant alguns "Tool boxes" especialitzats com: Lògica difusa, Xarxes neuronals, Estadística, Utilitats de graficació, Creació d'interfície d'usuari (GUI), Bases de dades. El resultat d'aquesta integració és una aplicació pilot anomenada RMADS (Rapid Manufacturing Advice System), el qual compta amb una interfície gràfica d'usuari que es divideix en tres mòduls:

- Requeriments generals de disseny. Aquest mòdul analitza els paràmetres usualment definits en les especificacions inicials de Producte, per exemple: tipus de material, toleràncies, acabat superficial, complexitat geomètrica, etc.
- Mòdul de costos. Aquest mòdul utilitza paràmetres d'entrada prèviament introduïts com: volum de peça, mida de lot i dimensions totals, per a realitzar càlculs mitjançant mètodes paramètrics i models basats en xarxes neuronals. El resultat és una estimació del cost per peça i també el cost estès per volums grans.
- Selecció de materials. Aquest mòdul mostra la natura iterativa del procés de selecció de materials, a través de criteris de "filtratge" o selecció, de manera que a cada iteració el nombre d'opcions sigui limitat a un nombre raonable d'alternatives.

A través de l'estudi d'un nombre de casos d'exemple, així com de peces mecàniques extretes de dissenys industrials, la funcionalitat del sistema és analitzada. En l'últim capítol s'estableix una discussió sobre la utilitat i viabilitat de la fabricació ràpida per a aplicacions industrials reals, així com les restriccions que poden aparèixer.

Mentre que el primer mòdul dedicat a l'anàlisi de paràmetres de disseny inicials, fa una funció de selecció preliminar, els mòduls restants del sistema RMADS es mostren més restrictius. Per exemple, els factors relacionats amb el cost mostren diferències més clares entre els processos candidats (principalment entre tecnologies metàl·liques basades en plàstics), mentre que el mòdul de materials mostra propietats funcionals d'interès sense ser afectat pel factor "costos".

La finalitat d'aquest sistema és proporcionar un "entorn basat en coneixement" per a la selecció de processos de Fabricació Ràpida, tenint en compte les necessitats especialment dels usuaris amb poca experiència en l'àrea de les tecnologies additives.

Tot i que l'aplicació pilot que s'ha desenvolupat no compta amb una interfície d'usuari elaborada, es considera que el sistema representa un pas endavant cap a un sistema estandarditzat per a la selecció de processos de Fabricació Ràpida. L'objectiu d'aquesta investigació és presentar d'una banda, una metodologia de selecció coherent i estructurada, i per l'altre costat, una aplicació prototip que pot ser usada com una eina educativa per a l'educació ja sigui tècnica o superior, en disseny industrial i selecció de processos.

Cal esmentar que encara que l'objectiu d'aquest projecte no és la "migració total" cap a la fabricació additiva (no encara), però un objectiu que sembla com suficient, serà el aconseguir que tant estudiants, com a persones alienes a aquestes tecnologies es preguntin: ¿I què passaria si ho fes d'aquesta manera?

## Resumen

La fecha oficial de la aparición del 'Rapid Manufacturing' se sitúa entre 1988, año en que la compañía estadounidense 3D Systems introducía el primer sistema comercial de Prototipado Rápido (RP del inglés Rapid Prototyping) a través de la tecnología de Estereolitografía, y 1992, cuando las primeras máquinas comenzaron a ser comercializadas, siendo adquiridas por centros de ingeniería a nivel mundial, iniciando así una nueva era de la fabricación.

Desde entonces han surgido un creciente número de estudios e investigaciones relacionadas con la llamada 'Fabricación de Forma Libre' (o SFFF del inglés Solid Free Form Fabrication). Uno de los estudios clásicos que la mayoría de expertos e investigadores han referenciado alguna vez en sus trabajos es el titulado 'JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan' publicado por la Asociación de Ingenieros de Fabricación de Estados Unidos (SME) en 1997, pudiendo ser considerado como una de las fuentes de información más completas y valiosas en el campo del Prototipado Rápido de la época. Desde entonces a la actualidad se han producido varios cambios en el escenario del RP, por ejemplo, algunas de las empresas pioneras en la introducción al mercado de tecnologías aditivas de fabricación tales como: BPM, Soligen, Helysis, Teijin Seiki han desaparecido o han dado un giro a su estrategia, por ejemplo, operando como un centro de asesoría tecnológica. Sin embargo desde 1992 a la actualidad, el lanzamiento de nuevos equipos y tecnologías de RP o RM ha continuado de forma ininterrumpida.

Es difícil dar un seguimiento a los desarrollos y el estado del arte de un área tan dinámica. Desde el inicio de esta investigación en 2004 hasta 2009, se han presentado algunos cambios en el paradigma de 'Rapid Manufacturing'. Mientras una cantidad importante de los esfuerzos de investigación hasta 2004 se concentraban en "prototipado", la industria se movilizaba hacia la 'fabricación'; mientras el tema de 'Prototipado Rápido' en la academia era tímidamente incluido en el curriculum de estudios de ingeniería, la industria creaba Asociaciones y consorcios de 'Fabricación Rápida'; mientras la academia y la industria se concentraban en encontrar aplicaciones industriales especiales (nichos), jóvenes emprendedores alrededor del mundo creaban nuevos modelos de negocio y servicios basados en las inusuales capacidades de los procesos aditivos.

A nivel local y regional el escenario no era distinto. Cuando el Dr. Carles Riba, director del centro de Diseño de Equipo Industriales de la Universidad Politécnica de Cataluña, propuso la idea de esta investigación, el objetivo final era más bien difuso. Fue necesario alrededor de un año de investigación de campo, consultas y entrevistas con expertos, asistencia a ferias y eventos industriales así como visitas a talleres locales y centros de ingeniería para afinar los objetivos de la investigación. Durante este mismo período se conformó la Asociación Española de Rapid Manufacturing, contribuyendo a clarificar cuáles son los intereses de investigación y el rol de la investigación universitaria en un contexto regional.

Rapid Manufacturing puede ser entendido como una colección de procesos de fabricación capaces de generar piezas funcionales directamente a partir de un modelo en 3 dimensiones. Esta pieza puede ser ya sea, modelada en un software CAD, o extraída mediante métodos de ingeniería inversa para obtener una geometría sólida. La mayor parte de los procesos de RM están basados en la deposición por capas de material, por ejemplo: sinterizado láser, curado por luz ultravioleta, agentes adhesivos, entre otros.

Las opciones de materiales en la actualidad son bastante reducidas ya que incluyen: polímeros (ABS, PA, Policarbonato, etc.) metales (acero inoxidable, aluminio, titanio y aleaciones), materiales similares a la escayola, cera así como un amplio rango de foto-polímeros. Recientemente las ventajas de la fabricación aditiva están siendo exploradas mediante materiales avanzados como: con funcionalidad gradual y formulaciones con formulaciones estructurales modificadas, sin embargo estos desarrollos han tenido a la fecha solo un reducido efecto comercial.

De las tecnologías del Rapid Manufacturing actualmente disponibles solo unas pocas son capaces de proporcionar propiedades mecánicas similares a las de procesos convencionales tales como moldeo de inyección, colada en arena, micro fusión, etc. De forma general, la naturaleza aditiva de las piezas producidas por Rapid Manufacturing provoca diferencias en la composición y comportamiento del material. Por ejemplo, algunas piezas fabricadas por este medio presentan un comportamiento anisotrópico especialmente cuando se fabrican con una orientación vertical, mientras que otros fenómenos como el 'escalonado' o la 'piel de naranja' suelen aparecer debido a diferencias en los parámetros de calibración y orientación.

La adopción de RM como una alternativa de fabricación para sectores como el de automoción, aeronáutica y médico, es especialmente complejo y al mismo tiempo de un alto interés, por lo tanto han recibido una atención especial por parte de la comunidad científica e industrial del RP y RM. No obstante, para otros campos con menores requerimientos de entrada los beneficios del Rapid Manufacturing sobre todo referentes a: libertad de diseño, y producción económica de series cortas o unitarias, actualmente constituye una ventaja competitiva. El reconocimiento de estas ventajas 'ocultas' sin embargo, avanza a ritmo lento sobre todo para Pequeñas y medianas empresas a nivel local, que no cuentan con la capacidad de realizar altas inversiones en materiales y equipos y por tanto tratan de ceñirse y optimizar las prestaciones de sus equipos actuales.

Los equipos de RM no son especialmente baratos, de hecho su precio es elevado especialmente para las tecnologías de procesamiento de metales equipadas con laser, así como para el sinterizado láser de polímeros. Es aquí donde los centros tecnológicos y de servicios muestran su capacidad para ofrecer servicios especializados ahorrando así a sus clientes los costes de propiedad y mantenimiento de esta clase de equipos. Sin embargo tanto los centros de servicio, prototipado y centros tecnológicos no han logrado comunicar de forma efectiva y a un público más amplio las ventajas de trabajar con Rapid Manufacturing.

La intención de este proyecto de investigación es ir más allá de lo logrado por los sistemas existentes de selección y comparación de procesos de Prototipado Rápido, mediante la introducción de una nueva metodología que tenga como único fin la 'Fabricación Final' de componentes. El sistema desarrollado incorpora algunas de las herramientas más recientes del campo de Inteligencia Artificial, de forma que sea posible lograr una metodología concurrente que incluya:

- Sistemas expertos, que se ejecutan durante el proceso de toma de decisiones con alternativas múltiples. Los sistemas expertos utilizan típicamente estructuras del tipo: IF-THEN-ELSE o CASE, de forma que las opciones puedan ser 'cribadas' especialmente durante las primeras etapas de la selección.
- Lógica difusa para la toma de decisiones. Usualmente en el ámbito de la fabricación, algunos términos lingüísticos o parámetros de tipo cualitativo son utilizados para definir estados o propiedades. Por ejemplo es común encontrar términos cualitativos tales como: 'buenas propiedades mecánicas' o 'alta tasa de absorberencia', en lugar de cifras y números puntuales. Por lo tanto es necesario contar con un método para traducir y gestionar dicha información. La lógica difusa ha sido adoptada como medio para

traducir términos de orden cualitativo a información cuantitativa de forma que a partir de estos datos pueda construirse un sistema de clasificación y ranking de procesos.

- Toma de decisiones Multi-criterio, agrupación (sumatoria) y clasificación. Durante la investigación se probaron diferentes métodos para la clasificación de alternativas y selección final a partir de vectores de orden cuantitativo con pesos ponderados. Para esta fin se adoptó la metodología propuesta por Lan et al. (2005) el cual se describe en el capítulo 5 de este trabajo.
- Redes Neuronales Artificiales. Estas han sido aplicadas para el modelado y simulación de algunos procesos de Fabricación Rápida previamente seleccionados. Por ejemplo, el proceso de Sinterizado Selectivo Láser se logró modelar utilizando Redes Neuronales con un algoritmo de "backpropagation", tomando como información base, los datos proporcionados por el software propietario del equipo. Esta red neuronal simula una máquina de sinterizado láser modelo DTM Vanguard, disponible en la FundacioCIM-UPC en Barcelona. Por otra parte el proceso de Fusión Selectiva por Láser ha sido modelado también mediante Redes Neuronales a partir del equipo Concep Laser M2, disponible en el laboratorio de Ingeniería mecánica de la Universidad Católica de Lovaina, Bélgica. Los modelos extraídos de estas simulaciones muestran una estimación del tiempo total de fabricación menor al 10% lo cual representa una mejora substancial respecto a métodos de estimación paramétricos.
- Finalmente se ha utilizado la técnica de bases de datos relacionales para la gestión y almacenamiento de información sobre materiales. Estas bases de datos han sido creadas en Ms Access, que proporciona la facilidad de acceso, filtrado, graficación y presentación de la información requerida. Esta información puede ser extraída automáticamente mediante llamadas ODBC, ejecutadas desde el entorno Matlab.

Para ilustrar el funcionamiento de las herramientas descritas en una forma integrada, se ha optado por desarrollar una aplicación piloto en Matlab, utilizando algunos Tool boxes especializados como: Lógica difusa, Redes Neuronales, Estadística, Utilidades de graficación, Creación de interfaz de usuario (GUI), Bases de datos.

El resultado de esta integración es una aplicación piloto denominada RMADS (Rapid Manufacturing Advice System), el cual cuenta con una interface gráfica de usuario que se divide en tres módulos:

- Requerimientos generales de diseño. Este módulo analiza los parámetros usualmente definidos en las especificaciones iniciales de Producto, por ejemplo: tipo de material, tolerancias, acabado superficial, complejidad geométrica, etc.
- Módulo de costes. Este módulo utiliza parámetros de entrada previamente introducidos como: volumen de pieza, tamaño de lote y dimensiones totales, para realizar cálculos mediante métodos paramétricos y modelos basados en redes neuronales. El resultado es una estimación del coste por pieza y también el coste extendido para volúmenes mayores.
- Selección de materiales. Este módulo muestra la naturaleza iterativa del proceso de selección de materiales, a través de criterios de "filtrado" o selección, de forma que en cada iteración el número de opciones sea limitado a un número razonable de alternativas.

A través del estudio de un número de casos de ejemplo, así como de piezas mecánicas extraídas de diseños industriales, la funcionalidad del sistema es analizada. En el último capítulo se establece una discusión sobre la utilidad y viabilidad de la fabricación Rápida para aplicaciones industriales reales, así como las restricciones que pueden aparecer.

Mientras que el primer módulo dedicado al análisis de parámetros de diseño iniciales, realiza una función de selección preliminar, los módulos restantes del sistema RMADS se muestran más restrictivos. Por ejemplo, los factores relacionados con el coste muestran diferencias más claras entre los procesos



candidatos (principalmente entre tecnologías metálicas basadas en plásticos), mientras que el módulo de materiales muestra propiedades funcionales de interés sin ser afectado por el factor “costes”.

La finalidad de este sistema es proporcionar un “entorno basado en conocimiento” para la selección de procesos de Fabricación Rápida, teniendo en cuenta las necesidades especialmente de los usuarios con poca experiencia en el área de las tecnologías aditivas.

Aunque la aplicación piloto que se ha desarrollado no cuenta con una interface de usuario elaborada, se considera que el sistema representa un paso adelante hacia un sistema estandarizado para la selección de procesos de Fabricación Rápida. El objetivo de esta investigación es presentar por un lado, una metodología de selección coherente y estructurada, y por el otro lado, una aplicación prototipo que puede ser usada como una herramienta educativa para la educación ya sea técnica o superior, en diseño industrial y selección de procesos.

Cabe mencionar que aunque el objetivo de este proyecto no es la “migración total” hacia la fabricación aditiva (no aun), un objetivo que se antoja como suficiente, será el lograr que tanto estudiantes, como personas ajenas a estas tecnologías se pregunten: ¿Y qué pasaría si lo hiciera de esta manera?

## Preface

Although the engineering projects department has included the topic of Rapid Prototyping as part of the first year courses there were not previous research projects developed in this field. Nor was it common to make them before 2004, therefore this research has been performed in different stages:

- A first stage of nearly one year has been performed at the Machinery and Equipment Design Centre (CDEI) of the technical University of Catalonia under the guidance of Dr. Carles Riba. During this time it was possible to have access to the collection of previous projects developed in this centre. The earlier publications achieved during this project were result of the consultancy of such material.
- A second stage was performed as a field research with an approximate duration of 6 months. During this time study was performed, entitled: Good Practices in Rapid Manufacturing from the original in Spanish: “Buenas Practicas en Rapid Manufacturing” available at <http://fpsgroup.googlepages.com/iniciativarm>. This work consisted on a series of visits, interviews with experts and surveys on the common uses, limits and opportunities foreseen in the field of RM. From this stage it was possible to achieve the first journal paper of this project: “Pursuing successful rapid manufacturing” published in summer 2008 in the Rapid Prototyping journal.
- The last stage has been performed since early 2008 at the Fundacio CIM centre. Where it has been possible to be in closer contact with RP/RM technologies and also has given me the opportunity to gain access to the field of funded projects, expert meetings and the attendance to congresses which have enriched the impact of this research.

A complete list of congress and journal publications is included at the end of the Appendix section. Additionally, along with a number of industrial visits during December 2008 it was possible to complete a short research stay at the Mechanical Engineering Department of the Catholic University of Leuven. Under the supervision of Dr. Kruth it was possible to have access to a Concept Laser machine to measure build time parameters, useful for the development of an ANN-based costing model. During this time it was also possible to visit two Belgian centres: the Layer wise company, a new spin-off of the KU Leuven, founded by Jonas Van Varenberg, former PhD fellow, and the Sirris centre in Liege.

I’m sure the contacts gained during these years will remain for a long time during my research career...hopefully!

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Fecha: Wed, 13 May 2009 18:31:55 -0600 [02:31:55 CEST]  
De: SiderWhite <siderwhite@worldnet.att.net>   
Para: RP-ML <rp-ml@rapid.lpt.fi>  
Asunto: [rp-ml] RP process selection matrix?

Dear rp-ml:

Just wondering if anyone has a good decision matrix for selecting the best RP process and material for a company's particular applications.

Any help or ideas would be greatly appreciated.

Best regards,

Glenn Whiteside

Message sent to the Rapid Prototyping mailing list. May 13, 2009

# 1. Introduction

---



## 1 Introduction

The Thesis Project “RMADS: Development of a concurrent Rapid Manufacturing Advice System” is framed within the research line: Technological innovation of product and process engineering, of the Engineering Projects Department of the Technical University of Catalonia. It also meets the research line on Small Series Production promoted by the Industrial Equipment Design Centre (CDEI-UPC) who has provided continuous support by providing sample case studies and technical information on potential applications of Rapid Manufacturing technologies.

This thesis project has been developed in parallel to other two projects aimed at the characterisation and automated selection of 1) surface coatings and 2) sheet metal processes for low volume production. The aim is to provide a general perspective of the fabrication of industrial parts produced in small batches. This is an inherent characteristic of the machinery and special equipment industry; hence the results obtained from this work might be harnessed in the search of more innovative means of production and design.

This work aims to explore the new possibilities offered by additive manufacturing methods that have been introduced since the early 90's derived from Rapid Prototyping technologies. Although some of these processes comprise already consolidated technologies, especially for automotive firms, service bureaus, engineering centres and related markets, their use as actual manufacturing methods for fully functional end-use parts is surprisingly limited and has not been embraced by the majority of the potential users. This opportunity loss may be even more significant for sectors where small series or unique parts are the only option.

The generalized lack of awareness of such opportunity is believed to happen due to a knowledge gap between the well know conventional manufacturing methods such as injection moulding, thermoforming, machining, casting, etc. and the new additive manufacturing methods. It is also true that new technologies of this type emerge every year; therefore it is necessary to establish a general frame where all (or at least those comparable) can be tracked and analyzed in order to be aware of their capabilities and virtual advantages.

The selection model developed in this thesis has adopted a concurrent engineering approach, as it tries to analyze different factors that affect the selection of processes and materials such as: general functional requirements, costs and technical feasibility, as well as other type of factors such as the freedom of design and possibilities for functional integration. The last two factors are implicitly studied throughout this text, as they have not been object of direct research, however by analyzing costing and viability criteria, different opportunities for harnessing the capabilities of Rapid Manufacturing have arisen.

### 1.1 Antecedents

The interest of this project, for developing a selection system with concurrent criteria for analyzing RM technologies has its origin in the common need for highly specialized parts in the special equipment and machinery sector where low production volumes must be paired with high quality and cost-effective manufacturing routes. Little research has been made regarding the selection of RM methods, however Rapid Prototyping has a long history of case studies and automated selectors whose main ‘logic’ has been extracted and adopted to this new scenario.

The transition from Rapid Prototyping (RP) to Rapid Manufacturing (RM) has produced a major shift on the way how products can be designed harnessing the possibilities of high complexity and multi-functionality of

additive methods, however. Many of them are not capable to compete in quality, price and productivity with the historically established processes. There is a group of technologies though, dating back from the beginning of the RP industry that have remained competitive and evolved as feasible solutions in those cases where the investment in moulds, matrices and tools in general is not justified due to the low number of units that are required by certain industries.

The already classic RP processes: SLA, FDM, 3DP, SLS were fundamentally devised to provide the industry with fast, precise and cost saving prototypes, depending on their final application and the details required. Their use was promoted specially by the aeronautic and automotive industries, which due to the large demand of prototypes have contributed enormously to the expansion of the RP capacities by creating the necessity of new enhanced materials with superior properties.

Likewise this fact has motivated an important amount of research, concluding that these technologies have a real future not only for the automotive and aeronautic sectors, but for the medical industry, academy, construction, entertainment, etc. Rapid Manufacturing has already become a widespread research line with a multitude of scopes: from software, virtual reality and simulation, to the study of materials, mechanisms, processes, and even the economic management, studies of viability and industrial prospective.

The term Rapid Manufacturing itself can be one of the most controversial definitions in industry as many alternative names have appeared in a relatively short period of time such as Free Form fabrication, layered manufacturing, 3D printing, etc. However it has not been possible to have a final consensus. While some experts assure that RM deals with the application of merely additive technologies for final products, others state that this concept may include every process that works in a fast way, including CNC, electro erosion, micro fusion, laser machining and mainly Rapid Tooling (RT).

The final goal for the RM industry is to achieve the point where fast, flexible, totally customized and economically feasible manufacture is possible; this is demonstrated by numerous examples such as customized seats and boards for automobiles, medical implants with biocompatible materials, or specialized parts for spaceships and military equipment.

The need for highly specialized, customized products in low quantities can be caused due to different factor:

- To operate in a market with a limited/ flexible demand
- To introduce a new product and evaluate the market response
- Unique machinery Designs, special parts or products
- To introduce product variations and expand the line of products
- Specialized applications such as medicine, micro cameras, sensors, etc.

The concept “small series” is also applied to those markets where the product lifecycle is short-enough for introducing product changes and innovations in each new batch or new edition. However several authors in the field of RM have described its limited use as “frustrating and surprising” based on the fact that only a reduced number of industries and sectors indeed apply them and harness their potential. This work hence, aims at developing a useful tool for the analysis, comparison and presentation of RM knowledge.



## 1.2 Definition of the research

Given the previous context, on one hand there is an important scientific activity and development of new applications for RM technologies, and on the other hand there is a generalized lack of knowledge from potential beneficiaries of these technologies, and the alternatives available on the market.

Considering that there is a significant amount of cases and industrial applications to validate the use of some RM technologies for the final manufacture of goods, as well as a growing number of materials apt for end use applications, it was detected a necessity to collect, process and validate the information available so that it can be translated into a useful tool for the better use of the existing RP and RM technologies, that are now under-utilized and under-profited. The main purpose is to develop a tool to evaluate the feasibility of certain products and RM processes currently available to be considered as a real alternative for the product manufacture from the conceptual design stage.

The feasibility should satisfy the following factors:

- Technical feasibility (regarding shape, aesthetical and functional requirements)
- Economical feasibility (approximate cost of RM processes for different batch sizes)
- Materials compatibility (suitable materials for accomplishing the requested function)

The initial approach for assessing the basic capabilities study of RM methods is by performing a process characterization. This means, the determination of key parameters and conditions for the process which result in a technically and economically feasible product. The study of successful cases of RM, previous research and the analysis of good practices of engineering centres that work with these technologies will help establishing such conditions to find the best configuration of process based on RM that responds to the initial product specifications.

Economical feasibility has been developed through a number of costing models suitable for the additive-type manufacture. To this respect, there is a difference between different costing model topologies according to the level of detail and the information available from the product. For instance while parametric models require a set of process and product parameters (e.g. volume, dimensions, process speed, etc.), analytical models require detailed information and highly specialized values. The sooner the process selection is performed in the design process, the lesser parameters will be available, therefore a series of artificial intelligence methods are proposed so that accurate estimations can be made, inferred by historic information.

Regarding materials, there are a number of previous studies and testing that tend to show the shortcomings of the use of RM materials such as low mechanical properties, unknown chemical resistance and poor environmental exposition, thus precluding their use for demanding applications. However this also means an opportunity to exploit those properties that do not necessarily mean a restriction. The development of a materials database is proposed so that material properties can be screened according to the real needs of the product.

### 1.2.1 Research Questions

From the previous overview a number of questions arise regarding the real capability of RM to be used as final manufacturing methods:

- Is it possible to build a part or reduced batches through RP equipment?

- Do RP technologies really have productive capacity?
- Is it possible to identify parameters whose user-dependent values affect fabrication capacity?
- Is it possible to use RM materials for end use products?
- Is it too expensive or is there a way to prove the RM economical feasibility?
- How are costs addressed in the RM and RP industry?
- What kind of products is more likely to be constructed with those methods?
- Is it possible to provide design guidelines to produce through RM?
- Does the designer really need design aids to profit RP to the maximum?
- Do local companies use RP for production?
- In which part of the design process is it proper to consider RP as a manufacturing technique?
- How would it affect the conventional design process?

The answer to all this questions will comprise the main body of this research.

### 1.2.2 Hypothesis

“It is possible, from the initial requirements of a small series product, to propose a systematic method for the selection of a Rapid Manufacturing Technique as a real alternative of productive process, and justify its application technically and economically”.

### 1.2.3 Secondary Hypothesis

- The characterization of RP processes allows the identification of key manufacturing parameters, useful to prove the technical and economical feasibility of parts
- There is a specific niche of products with aesthetical characteristics and technical requirements whose fabrication is feasible with RM
- The additive nature of RP processes can lead to the establishment of new design criteria that can overcome some current restrictions present in techniques likes DFM and DFA

### 1.2.4 Objective

The final objective of this thesis project is to develop a model for Rapid Manufacturing process selection and evaluation, which represents an aid for designers when considering RM as a productive alternative, thus widening their process, materials and design possibilities.

#### Particular objectives:

- Identify current requirements for products in the low batches sector and the chance to use RP for production
- To find the proper way to define part complexity in terms of RP and RM
- Clarify current RP systems limitations and define their real potential
- Develop an alternative cost estimation method that represents an alternative to current parametric models available from a number of sources.

### 1.2.5 Project outreach

As it has been expressed in the previous section this thesis work will be oriented to the study of Rapid Manufacturing processes. This study will be focused purely on ‘*additive or layered fabrication*’ as these methods share a basic principle regarding shape and fabrication possibilities, different to the rest of tooling-based parts. A consequent definition introduced in the first chapter will be the basis to understand the

technologies considered in this process. This implies that similar technologies such as Rapid Tooling, machining et al. will not be included in the analysis.

As the main focus of this thesis is the development of an expert system, physical and mechanical testing of specimens and sample parts is not being envisaged for this research. It will however be considered as part of necessary further research.

As the major contribution of this work is expected to be the design and introduction of concurrent selection methods, it is not expected to generate a fully functioning commercial system. However a pilot application will be developed which will be capable of running the different modules concurrently in order to show the functionalities proposed as objectives.

### 1.3 Research methodology

The proposed methodology is split into two main phases (Figure 1.1):

- 1) Theoretical framework
- 2) Classification and model development

The theoretical framework includes the activities of Literature search, research of suitable mechanisms and niche market products, suitable for additive production with RM methods. Most of the studied mechanical designs are provided by the CDEI centre of the Technical University of Catalonia, which is a specialized centre for the design of machinery and industrial equipment intended for low series production.

The state of the art on Rapid prototyping and Rapid Manufacturing will be extracted from a number of sources depicted in the diagram shown below. It goes from a general search on RM process capabilities, to a detailed process-intensive description of RM implications.

One important part of technical information regarding good practices, can only be obtained by the work and consultation with technicians and experts on the field; therefore a field study on best practices in RM has been performed among regional research centres, service bureaus, Universities and technological centres which count with sufficient amount of expertise on the field. The result of this study has provided on the one hand, first hand information about parameters settings, technical difficulties, cost assessment and a global picture of RM business. On the other hand it has provided an invaluable contact with the industrial sector which has greatly enriched not only this work but the ideas for future applied research. A direct result of this interaction can be seen on the journal paper entitled: "Pursuing successful Rapid Manufacturing. A user's best-practices approach" published on the summer 2008 in the Rapid Prototyping Journal.

The second stage that comprises the model development has been split into four sections:

- The research and comparison of existing models for RM costing assessment, along with the development of enhanced costing models.
- The research and comparison of previous RP selectors, aimed at extracting the features and functionalities of interest to be included in the new proposed models.
- Data gathering on RM machines, parameters and technical information in order to use a number of Artificial Intelligence tools:
  - Fuzzy logic- For handling linguistic and un precise terms
  - Expert system- In order to design a rule-based system for decision making
  - Neural networks- Utilized for making a cost estimation module based on historical information
- Compilation of RM materials information and development of a relational database.

The next figure describes the overall research methodology followed during this research. The first scheme shows the preliminary research and information gathering phase with an overview of data sources and the databases developed. The second scheme shows the overall RMADS system design which includes the three main modules and the different elements than comprise the systems logic.

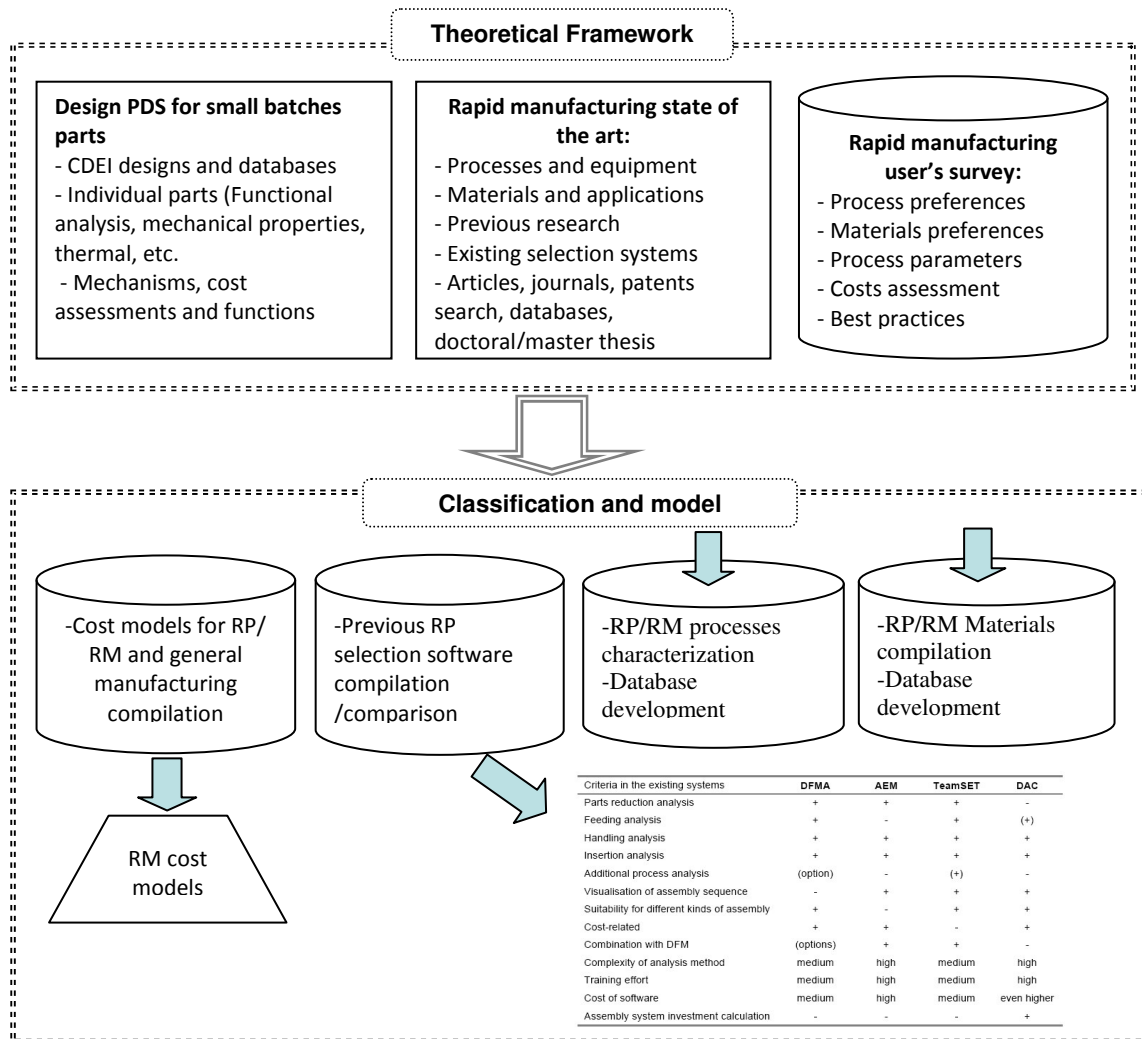


Figure 1. 1 General methodology scheme

Figure 1.2 shows a basic scheme for the expected general development of the RMADS system, as it includes the different modules comprising the system and their interactions. It can be seen how the Material costs and General design requirements are interrelated according to user preferences, while the costing module is independently driven. The methodology illustrated in this section aims at presenting a draft planning of the overall system resulting from this thesis project.

## Development of the RMADS system

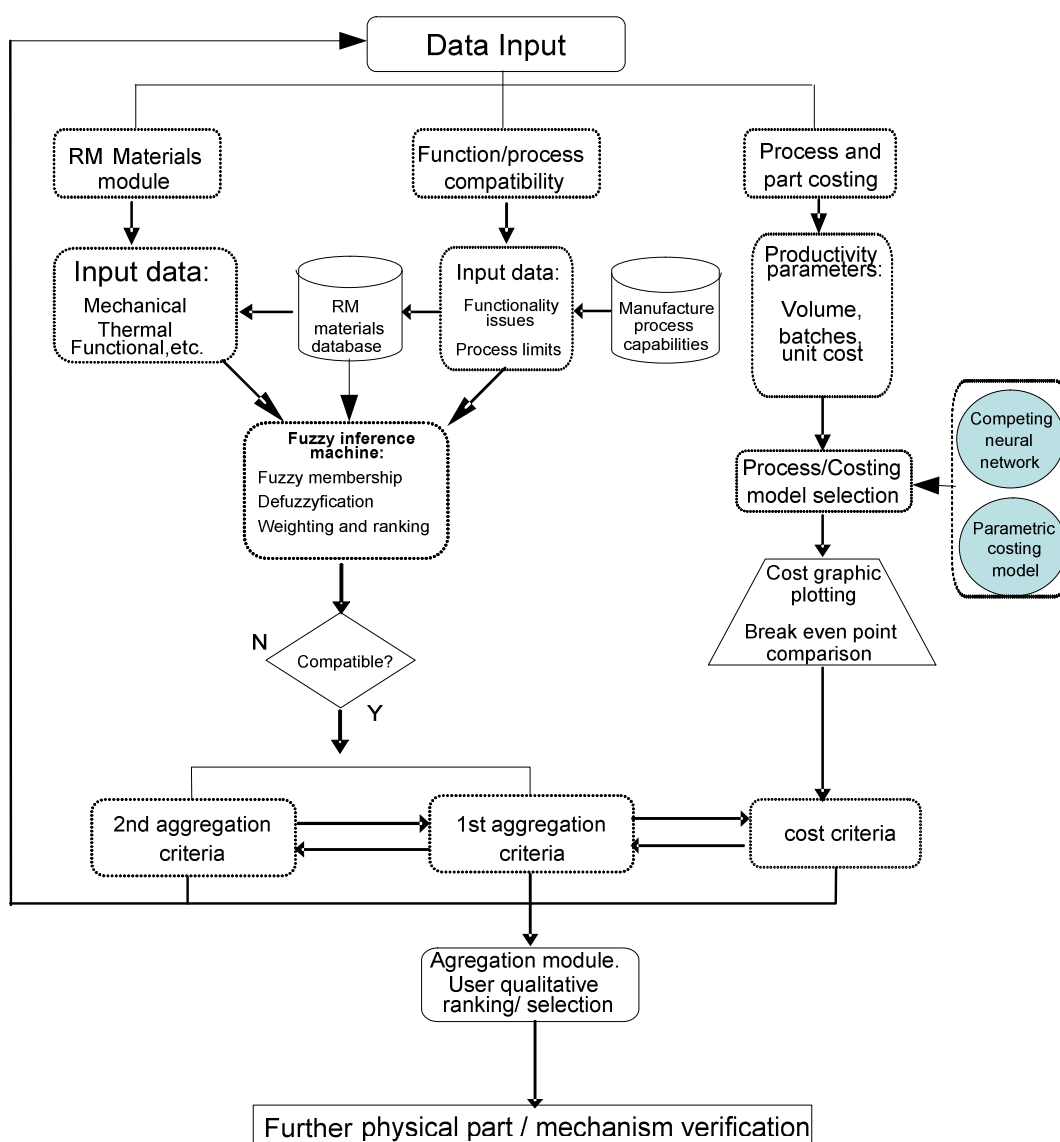


Figure 1. 2 General scheme of the RMADS system

## 1.4 Thesis outline

Following the order stated in the above index, Chapter 1 gives an introductory explanation of research needs and intentions regarding Rapid Manufacturing technologies.

Chapter 2 is devoted to presenting the state of the art on RM processes, important definitions, as well as a number of trends and applications on different sectors.

Chapter 3 provides an insight into the actual capabilities and main features of RM processes. This includes process and material related issues which influence the final consideration for fabrication. The classification of RM technologies is also embraced so that their main mechanisms can be identified. At the end, a number of characteristic features of additive processes are described.

Chapter 4 outlines the RM process selection system denominated RMADS (Rapid Manufacturing Advice System). This section describes a general picture of the different modules to be developed in further chapters.

Chapter 5 can be considered the core of this research as it starts with the development of the selection logic for the first module (General requirements) and it also makes an overview of previous RP selectors, pointing out their main features and implications. The results obtained from this section have generated an important number of publications which are included at the end of this document.

Chapter 6 makes an exhaustive review of costing methods applied to RM methods. This section is necessary so that the adoption of costing models for the RMADS system is well justified.

Chapter 7 describes a Neural-network-based approach for the optimization of cost estimation models, which has been deployed for the SLS and SLM technologies. This chapter analyses the performance of such methods compared to previous parametric estimators in order to provide accurate estimates based on historic part information.

The issue of Materials selection is studied in Chapter 8 as it discusses the relational databases approach adopted for the model. It also includes a description of available knowledge on RM materials and the shortcomings when analysing this data.

Chapter 9 presents a number of case studies where the use of the RMADS system is illustrated. The case studies belong to real mechanical parts developed by local engineering centres, where the use of RM processes for conventional designs is evaluated. This chapter has a core importance as it is shown how RM may not be a valid method for many designs; however with the proper design optimization they may become potential candidates for manufacturing.

Finally Chapter 10 presents the conclusions of this project discussing a number of contributions and findings made during the research period.

## 2. State of the art

---

### *Abstract*

*This chapter introduces the concept of 'Rapid Manufacturing' and also discusses some alternative definitions used for this term. A brief review on the evolution of these technologies is also presented specifying the main trends for its future development.*

*A general description of the most widely used technologies is included, along with the main fields of applications, pros and cons of additive technologies, so that the reader can have a previous background before introducing the subject of RM selection.*

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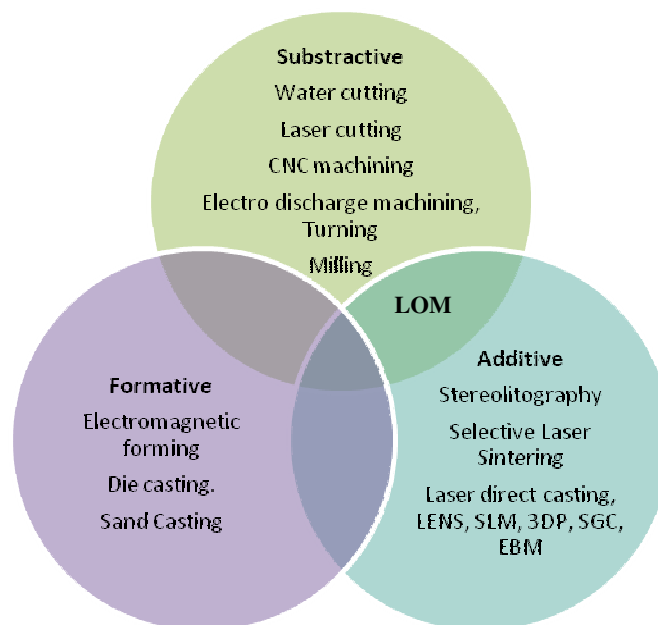




## 2. State of the art on Rapid Manufacturing

Defined with a variety of terms such as: Direct Digital manufacture,(DDM), Additive manufacture, e-manufacturing, Solid Freeform Fabrication (SFF) among some others, Rapid Manufacturing (RM) is the natural next step of the currently well known Rapid prototyping (RP) processes. Its definition varies worldwide; while for certain sectors it is defined as the use of computer automated additive manufacturing processes to construct fully functional end-use products or components (Platform 2006), for others Rapid Manufacturing includes not only additive methods but also a number of conventional techniques, such as Rapid tooling, High Speed Machining, Die less forming or laser machining to name a few (ASERM 2006).

Since the processes applied under the denomination Rapid Manufacturing are quite diverse, they can be classified into three different types of technologies commonly used for RM purposes:



**Figure 2. 1 Interaction of different RM technologies (Steen 2003)**

- Additive processes: where material is manipulated so that successive layers are deposited to form the final part. That is the case of technologies such as laser sintering, solid particles or binder deposition, paper sheets bonding, or cord resin dispensing between some others.
- Subtractive processes: material is successively removed from a solid block until the desired shape is reached. (High Speed Machining, milling, grinding, machining in general, EDM, etc.)
- Formative processes: mechanical forces are applied to form the desired shape (Die less Forming, Injection Moulding, etc.)

Steen (2003) illustrates in a Venn diagram (Figure 2.1) the interaction among the three typologies described above. It can be noticed that one RP process (LOM) is located right in the intersection between additive and subtractive methods due to the nature of the process for removing support material.

Due to the diversity of the technologies implicated, the definition of RM considered for the purpose of this work is as provided by Wohlers (2006):

*“Rapid manufacturing is the direct production of finished products or parts using additive fabrication techniques”*

This assumption has been also embraced by a considerable number of experts in the field, (Campbell and Bernie 1996; Hague 2003; Grimm 2004; Hopkinson, Hague et al. 2005; Hopkinson 2006) assuming that RM refers exclusively to additive methods most of them comprising “layer” manufacturing techniques. However there is a new yet to come generation of RM processes which will be characterized by higher speed, improved material consistency and versatility which are inspired in the current Printing systems (Dickens 2002). Therefore the term 3D printing is also common when referring to final additive fabrication.

### 2.1 The evolution of Rapid Manufacturing

Although its origins can be traced back to the 19<sup>th</sup> century with Topography and Photo sculpture as predecessors (Prinz, Atwood et al. 1997) the first patents for early attempts of direct additive fabrication were issued until the mid 20<sup>th</sup> century. In 1951 a Stereolithography-like technique, was introduced which through a system for selectively exposing a transparent photo emulsion in a layer wise fashion, solidified the material in layers, where each layer came from a cross-section of a scanned object. Later advances included selective three-dimensional polymerization of a photosensitive polymer and another process based on solid particles melting by means of a laser or electro beam (SME, 1997). However the official commercial success and activity of Rapid prototyping started in the late 80’s with Stereolithography (SLA) being introduced by the American company 3D systems (2007). This process based on the additive sequential deposition of thin photopolymer layers was soon accompanied by different approaches such as the Selective Laser Sintering (SLS) developed in the University of Texas at Austin, which is based on sequential deposition of laser sintered powder particles (Decker 1986). Other processes also emerged such as Laminated Object

Manufacturing (LOM) based on the superposition of paper sheets joined by a special binder, between some other additive like technologies which by the early 90’s set ground for the development of RP and its widespread usage.

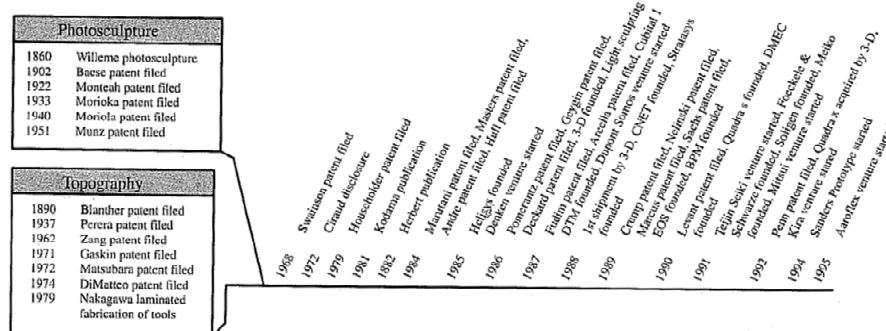


Figure 2.2 Rapid Manufacturing time line (Prinz 1997)

The previous time-line (Figure 2.2) shows major RP developments up to 1997. While some authors establish 1992 as the birth of Rapid Manufacturing industry it may be worth noting that it was until the late 90’s when this concept started to grow. The first specialized equipment for RM started to appear between 2000-2005. Within this period a massive introduction of new technologies and manufacturers has taken place however this has contributed to the specialization of RM technologies; while some equipment is being addressed to aesthetical and mock up applications (Zcorp, Desktop Factory and some 3D systems product lines) others are being addressed to the jewellery and medical markets (3D systems, envisiontec,

Nextfactory)<sup>1</sup>. For the next years there is a growing tendency towards the ‘*democratization*’ of 3D printing as a growing number of independent developers are launching RM solutions based on basic deposition techniques such as the Fab@home (Malone 2009) and the RepRap project (Bowyer 2009). Following such developments, commercial equipment manufacturers are following the trends of low cost RM equipments; as a result new product launches from 2008 onwards are comprised on 3D printing equipment with sell prices between 10,000- 15,000 €.

The history and development of RP processes is in depth covered by a number of recommended sources (Jacobs 1992; Freitag 2003; Hopkinson, Hague et al. 2005; Wohlers 2006). The report published by SME titled *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan* (1997) provides information on the development and evolution of Rapid Prototyping from the early inventions until the mid 90ths with exhaustive data on issued patents and technology developments. Jacobs (1992) launched one of the first books devoted to RP technologies with a special emphasis on the Stereolithography process. The annually published Wohlers report (2003, 2004, 2005, 2006) is considered as the official voice of the RM industry, including extensive information on the RP industry development overtime and future trends of the market.

On individual Rapid Prototyping technologies documentation, online resources are more recommendable since the information contained in books, articles and brochures is prone to rapidly become obsolete and new RP&M processes emerging everyday might be more easily tracked electronically. (CASTLE-ISLAND 2007) holds a wide background data not only for RP but for Rapid Tooling and Manufacturing as well. Technology info is accompanied by industry releases and patent documentation to keep track of the latest developments. Other commonly cited online resources include efunda (2007) thought only useful for process basics. The European RM-Platform (2006) includes case studies uploaded by regional research centres while other organisations like the SME Direct Digital Manufacturing community (2007), The Global Alliance for Rapid Manufacturing (GARPA 2007) or regional Rapid Manufacturing association such as the Spanish RM association (ASERM 2006) usually include technology descriptions and basics of available processes, case studies as well as contact details of service bureaus and equipment providers.

Though not extensively covered, the field of RP has been gradually included in academic engineering design and manufacturing literature. This is the case of (Dieter 2000; Ulrich and Eppinger 2003; Ashby 2005) and other specialized manufacturing handbooks such as those from SME and ASM (ASM 1997; Geng 2004).

While these books represent a starting point, much of the important details of rapid prototyping are available only in papers, patents, master and Doctoral Thesis or proprietary corporate documents (Kietzman 1999). Some good technology reviews are provided by Kruth (1991), and Levy (2003). However academic research and developments may be found in specialized conferences and events. The International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP 2007) hosted by the School of Technology and Management of Leiria, Portugal, the Annual Solid Freeform Fabrication Symposium hosted by the University of Texas at Austin or the International User's Conference on advanced Rapid-Applications organised by the Fraunhofer network in Germany are examples of specialized research paper sources.

### 2.3 Some concepts and definitions

Rapid prototyping has been extensively defined by different authors however most of them coincide in the basic principles: “RP is a collection of technologies driven by computer aided design CAD data for producing physical models and parts through an additive process” (Grimm 2004). Its main use is the generation of

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<sup>1</sup> A thorough review of individual technology developments and their niche markets is included on the Wohlers Report (2006-2008). Another highly recommended source for upto date information of emerging technologies and their technical features might be consulted on the RP & RM machine matrix available on the TCT magazine website: [www.time-compression.com/img/static/2008RP&MMachineMatrix.pdf](http://www.time-compression.com/img/static/2008RP&MMachineMatrix.pdf)

prototype parts and products for aesthetic or functional evaluation and also as an aid for the indirect production of end use pieces by means of moulds and other tooling elements, however the same definition is valid for RM. Although the term “Rapid” may suggest instantaneous fabrication, it is an ambiguous name since depending on the technology, the total build time may vary from minutes to days, therefore it must be clear that Rapid refers to the whole cycle of a prototype generation from concept to presentation, not only to the construction phase itself. Some of the most widely known and commercially successful RM technologies are briefly defined.

### 2.3.1 Stereolithography (SLA)

This was the first RP process to appear during the end 80’s. It is based on a layer wise curing of photopolymer to build a final prototype part (Figure 2.3). Each layer is fabricated by scanning a laser beam, guided by a moving mirror, to cure selected parts of a thin film of a liquid photo-sensitive resin. The scanning system is driven by an STL file created from a CAD model of the object. When one layer is complete, the part is lowered on a platform into the resin bath (typically by 0.1 mm) to that a new layer of liquid resin can be wiped across its surface. Post-curing is needed to completely solidify the prototype.

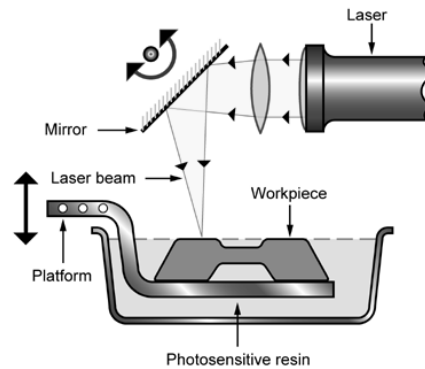


Figure 2.3 The SLA process (GRANTA 2007)

### 2.3.2 Selective laser sintering (SLS)

It operates on the same principles as Stereolithography, but uses a fine heat-fusible powder (a thermoplastic or wax) which is fused together by a scanned laser beam, layer by layer, to build the model (Figure 2.4). The surface is stepped as in SLA, requiring some finishing. Powders of ABS, both unfilled and glass-filled Nylon, polystyrene, and investment casting wax can be sintered. Nylon-based models can be functional with snap fits, screw threads and living hinges. This is one of the most studied processes due to the diversity of materials and possibilities for mixing powders to vary final properties.

The same principle is used for the laser sintering of metals, in this case when the model is built the very porous part is infiltrated with liquid bronze, which wets and is drawn into the porosity giving a fully dense product, with complex external and internal shape (such as cooling channels) that can be used as a die for injection moulding and die casting.

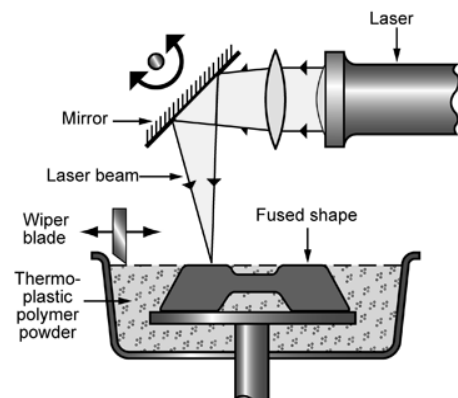


Figure 2.4 The SLS process (GRANTA 2007)

### 2.3.3 Fused Deposition Modelling (FDM)

In this process a fine stream of thermoplastic (wax or metal could also be used) is deposited by a two-axis heated extrusion head. Semi-liquid thermoplastic material is extruded and then deposited into layers, typically 0.1 mm, one layer at a time starting at the base (Figure 2.5). This builds the model vertically on a fixtureless base. Successive layers adhere together through thermal fusion. The FDM process requires no post curing enabling multiple versions of a part to be created within a short time frame. Materials available for use in the process include ABS and Nylon.

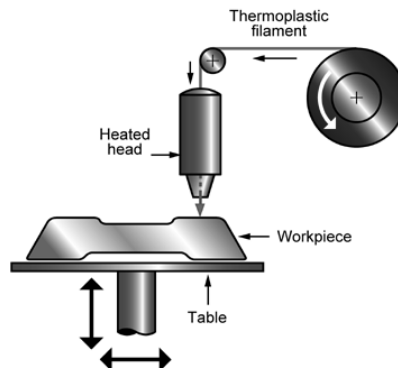


Figure 2. 5 The FDM process (GRANTA 2007)

### 2.3.4 3D Printing

This technology draws on the mechanism of ink-jet printers to build up successive layers of a prototype or model. Instead of ink, the print-head deposits thermoplastic polymer that quickly sets (Figure 2.6). A print head of 96 jets orientated in a linear array gives a print density comparable to a 300dpi printer. As with other rapid prototyping processes, a CAD solid model of the part is required. The attraction of 3-dimensional printing is that it uses multiple jets, greatly increasing the speed at which the model can be built.

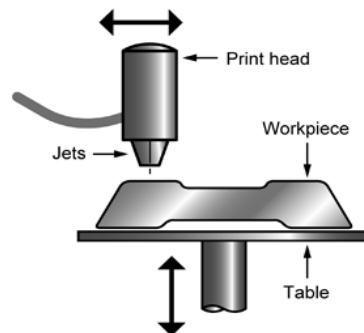


Figure 2. 6 The 3D printing process (GRANTA 2007)

### 2.3.5 Selective Laser Melting (SLM)

SLM uses a 40 $\mu$ m beam spot fibre laser to fuse small particles of metal powders into a mass representing a desired 3D object (Figure 2.7). The laser selectively fuses powdered material by scanning cross-sections generated from a 3D CAD model of the part on the surface of a powder bed.

After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed in a process similar to SLS. The SLM system has a special vacuum processing capability, allowing oxygen sensitive materials, such as titanium, to be processed.

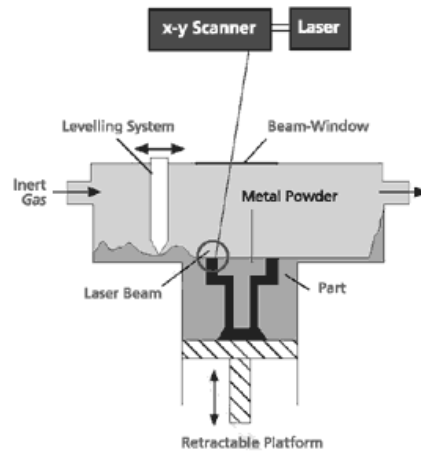


Figure 2. 7 The SLM process. Source (MTT Technologies Ltd)

### 2.3.6 Electron Beam Melting (EBM)

A recent process commercialized by the Swedish firm Arcam AB. In this process a 0.1 mm thick layer of metal powder is spread across the build platform (Figure 2.8). A 4 kW electron beam gun then preheats the layer using a relatively low beam current and a relatively high scan speed; it lightly sinters the metal powder to hold it in place during subsequent melting at higher beam powers.

After that it imparts heat to the part that helps reduce the thermal gradient between the melted layer and the rest of the part. By maintaining a more consistent overall part temperature, built-in residual stresses that would otherwise tend to warp the metal part are reduced. The build platform is lowered by an amount equal to one layer thickness, a new layer of metal powder is spread, and the process is repeated until the part is complete. This process has the capability for processing metals such as Stainless Steel, Titanium and other alloys.

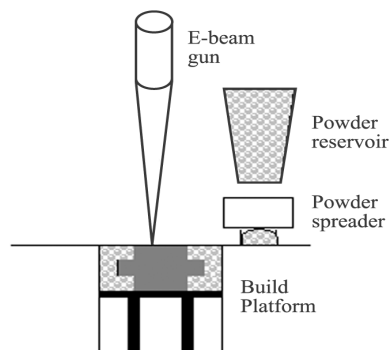
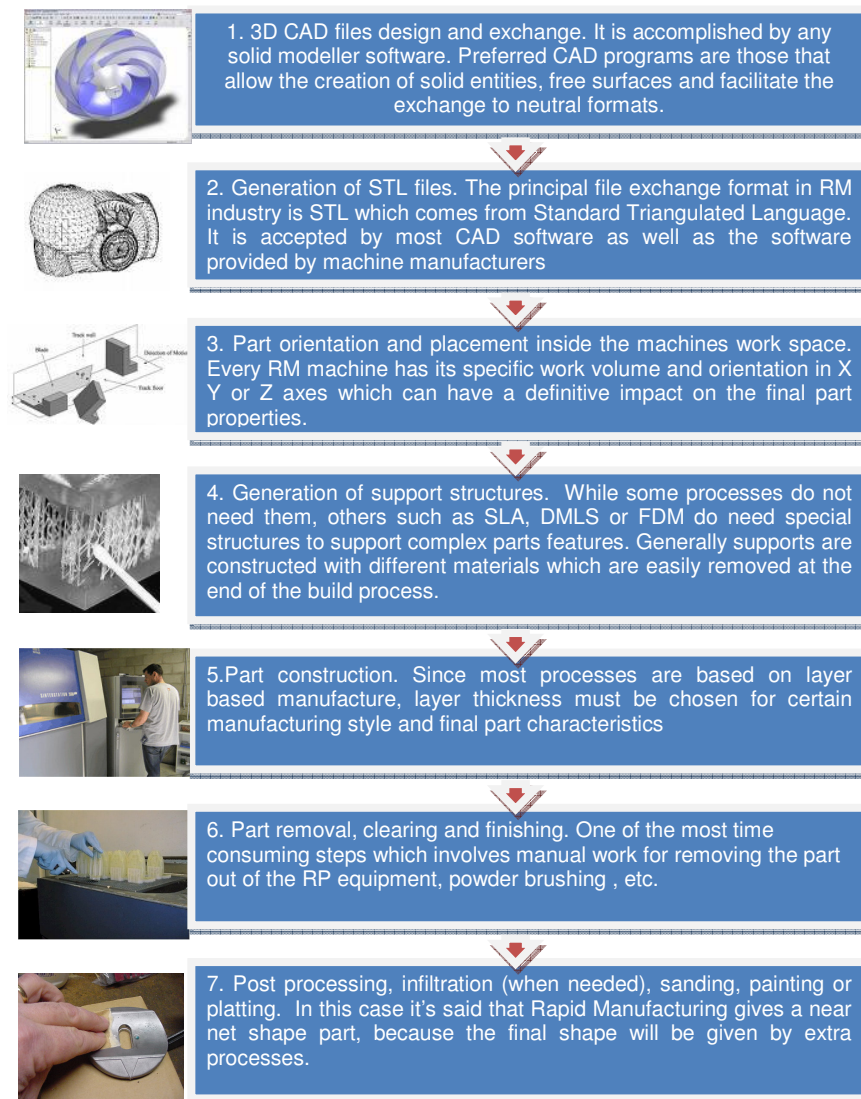


Figure 2. 8 The EBM process (CASTLE-ISLAND 2007)

Although there are currently over 30 different additive processes and even more on developing phases (Raja, Zhang et al. 2005; Wohlers 2006) only a few of them are commercially available and fewer have been applied to final manufacture of end use products. However the continuous research on these technologies shows an important potential to expand their field of application, to go from prototyping to real manufacturing. A more detailed description of the technologies described above is well documented in a handful of sources (Jacobs 1992; Pham and Gault 1998; Freitag 2003; Grimm 2004; ASERM 2006; Wohlers 2006).

## 2.4 The general RP and RM process

All RM processes contain different building parameters and enabling technologies however due to the layered nature of their mechanisms it is possible to establish a general frame of fabrication based on generic steps from designing and file export until fabrication (Figure 2.9).



**Figure 2. 9 The RM general process**

## 2.5 Current applications and perspectives of RM

The application of RM has been usually linked to low volume-niche applications, especially when the complexity of the part is such that it cannot be produced by other means of fabrication. Nevertheless RM is not intended to replace conventional processes as there are multiple capabilities and materials that cannot be handled yet by additive technologies and there are a number of parameters affecting productivity such as:

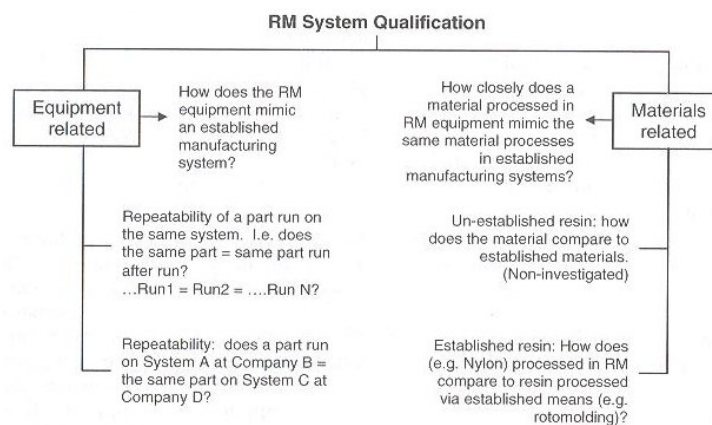
- A reduced build size
- Moderate to low speed
- Necessity for post-processing

There exists however a number of fields where the application of RM technologies is undoubtedly appropriate. RM is being applied in a number of sectors which on the one hand show their technical feasibility, and on the other their economical feasibility not only for small series but for serial production when volumes and the mix of products are smartly managed. Some sectors include aerospace, medicine, art and leisure, sports and other such as luxury goods which in some cases are not cost sensitive.

## 2.6 Sectors currently adopting RM

### 2.6.1 Aerospace

The aerospace industry has been one of the early adopters of rapid manufacturing technology. Aircraft components produced in small quantities often include complex-intricate features and must also meet stringent requirements (CASTLE-ISLAND 2007). Although this is a cost sensitive field, the price factor is often regarded as secondary to performance and security. Recently companies like British Aerospace or Northrop Grumman have introduced process-material qualification schemes for RM to ensure rapid manufactured parts comply with the strict sector regulations (Hopkinson, Hague et al. 2005). An example of such qualification scheme is shown on Figure 2.10.



**Figure 2. 10** RM decision tree for the aeronautical industry. (Wooten 2005)

Some already tested technologies in this field include: SLS, SLA and FDM (Fox 2005). Rapid Manufacturing for metals has also found a niche application in aerospace. Some already in-use RM parts are: housings for electronics, air ducts, wind tunnel models, and on-demand warehouse parts. It's expected that further improvements in materials will guide to metal, ceramic or graded materials introduction as well. Future application of RM includes development of jet engine components such as turbine blades with nested sensors and other complex parts.

### 2.6.2 Automotive

One of the early adopters of RP was Chrysler (Wohlens 1992) that undertook a quality quantification among different RP processes available by 1992 including: SLA, LOM and SLS. The parameters included machine build-time, overall cost, post-process needed and quality for a sample benchmark part however there was not a "clear winner". A number of recent works describe different applications of automotive components produced with RM.

Volker, Christof et al. (2004) showed the benefits of developing spare-customized parts for the automotive sector by studying the case of a Luxury car rear arm rest (Figure 2.11). The authors illustrated the difference between mass-produce the product vs. the alternative of SLS which showed far more convenient in terms of tooling and initial investment. However it was mentioned that SLS was an unknown method for the engineering and manufacturing departments.



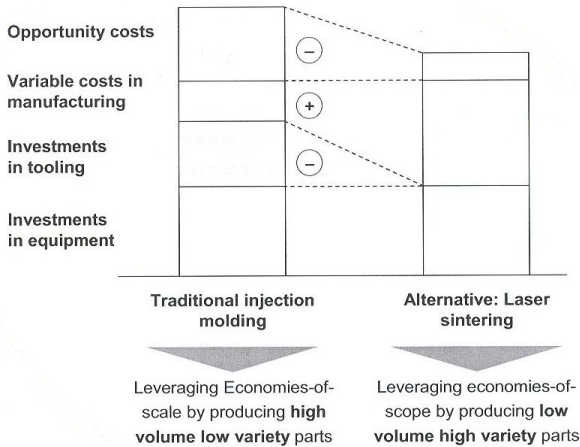


Figure 2. 11 Comparison between SLS and IM for a typical automotive component (Volker, Christof et al. 2004)

Sapuan (2005) and Cooper (2001) also illustrate case studies of the comparison of RM methods for the development of automotive components; while Sapuan investigated the feasibility of using SLS for a clutch pedal, Cooper showed a comparison of RM alternatives to generate investing casting models for a fuel pump housing (Figure 2.12).

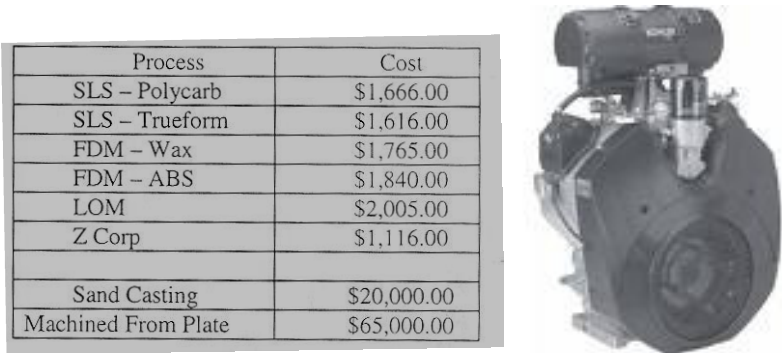


Figure 2. 12 Fuel pump cost comparison. (Cooper 2001)

Vilaro, Abed et al. (2007) described the development of a water-pump for motor sport cars fabricated with an Aluminium alloy (AlSi10Mg) on a Trumpf SLM machine. Results show a cost effective solution for a one-off part and a preliminary optimal performance (Figure 2.13).



Figure 2. 13 A water-pump built by the SLM process(Vilaro, Abed et al. 2007)

Some pioneer companies like Delphi and Ford have made some efforts to identify economic break-even points for conventional and rapid manufactured components while others like MG Rover (U.K.) a classic RM user has already included laser-sintered parts for some automotive applications such as customized front panels, buttons and internal parts are frequently found in “high standard” brands. However not all industrial applications are disclosed or published.

Formula 1 racing has experienced an almost seamless move from using additive fabrication for prototypes to using the same machines for end use purposes (Wohlers 2006). Wind tunnel and prototype components were quickly followed by race-useable parts made by RM such as electrical housings and aerodynamic parts. While for motor sports the use of RM and its customization capabilities is a reality, for the mass-commercial automotive sector, customization is not yet seen as a clear business advantage. To this respect some projects specially EU funded (EC 2004) have been launched in order to find potential business opportunities due to customization. The Foresight Vehicle Initiative (SMMT 2004) is intended to explore this alternative for future developments which foresees a more widespread use of virtual prototyping for validation and testing, letting the manufacturing phase of unique personalized components to the end of the process. Another Technological Foresight report edited by OPTI (Observatory for Technological and Industrial Prospective) in Spain (Garcia 2001; OPTI 2002; OPTI 2004) predicted a generalized application of RP technologies for the period 2000-2005 and advances in multi-material fabrication for the period 2006-2010. Also the EU funded Custom-fit project (Valero 2004) aims at the identification of niche markets for rapid manufactured customized parts with the automotive sector as one of the candidate scenarios.

### 2.6.3 Medical applications

Several medical fields find in RM an alternative for developing high-value tailored products. From the well known customized hearing aids from Phonak<sup>2</sup>, to the application of RM for bone reconstruction, artificial limbs, drug dispensers and highly specialized laboratory devices, the application of RM into medicine seems limitless. Because of the potential economic and performance advantages this is one of the most research-intensive application areas of RM.

Some key applications include in vivo implantation products, external devices and prosthetics, surgical fixations, tools and drug delivery devices. Harris and Savalani (cited in Hopkinson, Hague et al. 2005) list a number of activities where RM is being used coupled with additional medical technology such as X-ray computer tomography or magnetic resonance:

- Pre-operative planning
- Pre-forming of fixation components
- Manufacture of surgical guides and templates
- Simulation or surgical procedures

Orthodontics is yet another medical application especially for oral implants which has guided to the development of specific applications such as SimPlant and SurgiGuides from the company Materialise<sup>3</sup> which are intended to aid in the process of implant planning.

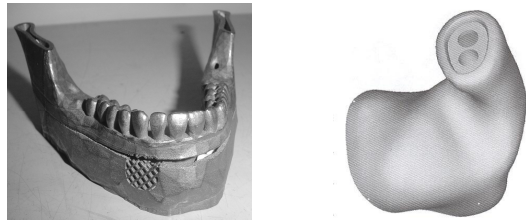
Also metal RM technologies have found a niche market in medical applications specially for facial bone reconstruction and development of biocompatible metallic implants (Vandenbrouche 2008). There is currently a growing interest for developing “in vivo” devices with different RM processes. Such devices include scaffolds, plates, screws, bone fixations, etc. which establish strict requirements in terms of

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<sup>2</sup> <http://www.phonak.com>

<sup>3</sup> <http://www.materialise.com>

biocompatibility, sterility and good performance. The advantage of RM is the possibility to control the internal shape of structures, compositions and external roughness however to date few RM materials provide the required properties. Two typical sample designs made with RM as shown on Figure 2.14 and 1.15.



**Figure 2.14** Customized maxillofacial prostheses design. KU Leuven 2008 and Hearing-aid shell with internal holes made (Siemens Hearing Instruments Inc.)

#### 2.6.4 Consumer products and leisure

Due to the ability to produce complex shapes with apparently no geometrical restrictions RM has been applied to several artistic and fashion design cases (Figure 2.19). The company Freedom of creation<sup>4</sup> based in Netherlands and dedicated to the design of decoration articles, lighting accessories, textiles and special edition products with a business model specially based on the SLS process of Polyamide. The creativity applied to the field of RM has also lead to alternative business models that did not exist a few years ago. Some examples are Shapeways<sup>5</sup> and Ponoko<sup>6</sup>, two web-based companies that allow users to find 3D designs, submit self-made designs or simply buy objects made out of digital cyber stores (other users). However more sectors are actively using RM.



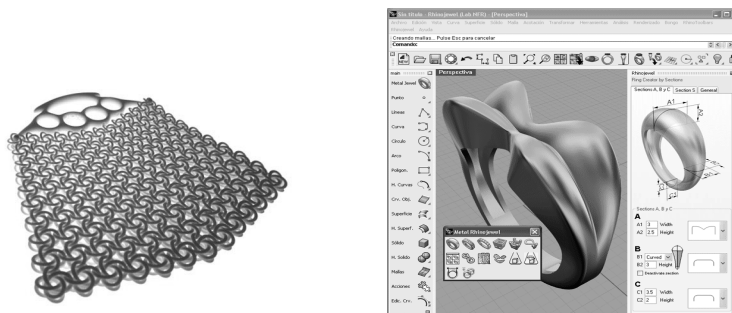
**Figure 2.15** Individual set manufacturing process chain for each patient: a) dental impression, b) digitised data elaboration, c) STL forming tool data, d) tooling sets on SLA 7000 system, e) thermoformed biocompatible transparent plastic bridge, f) bridge use in mouth (Levy 2003)

<sup>4</sup> <http://www.freedomofcreation.com/>

<sup>5</sup> <http://shapeways.com/>

<sup>6</sup> <http://www.ponoko.com/>

The jewellery field has attended the birth of a new generation of machines specialized in Photopolymer and castable resins for the almost automated production of jewels and accessories. That's the case of some RM machines such as Objet, Solidscape or 3D Systems Invision which are coupled with specialized jewellery design software like 3Djewel Design, Art CAM or Tec Jewel to generate low volume production of customized accessories. Reeves (2008) makes a fine description of some entertainment and recreational applications of RM where the user is in charge of defining or even designing its own personalized character. However as the author describes, a new issue arises regarding the intellectual property of characters when they are designed within a proprietary gaming or simulation environment. Drstvensek and Dolinsek (2008) include a number of interesting case studies of product design by embedding the user requirements and preferences within the design process.



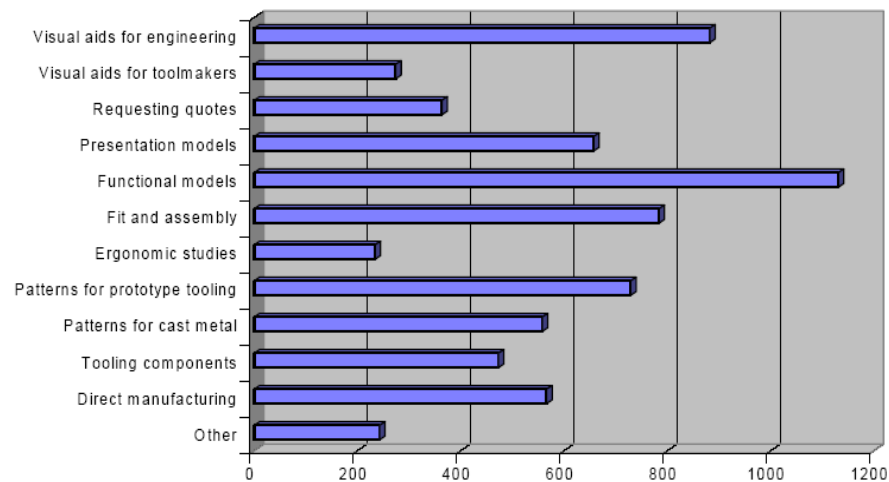
**Figure 2.16** Laser sintered purse Source (left) (<http://www.freedomofcreation.com/>) and Screenshot of the Techjewel software (right) ([www.Techjewel.com](http://www.Techjewel.com))

## 2.7 Drivers towards Rapid manufacturing

Even though the advantages and precision of emerging RM processes aims at more specialized applications such as micro, nano-fabrication and electronic component design, more time is needed to go from research to widespread industry cases. Until certain issues can be solved such as material properties, process repeatability, material costs and basic industry standards RM will have a slow impact in industry. Market tendencies such as reduced products life cycles, mass customization of consumer goods and shorter time to market are pushing however the development and improvement of current RM systems. The tendency is to become one reference process for low volume high value manufacture especially for specialized products in highly competitive markets.

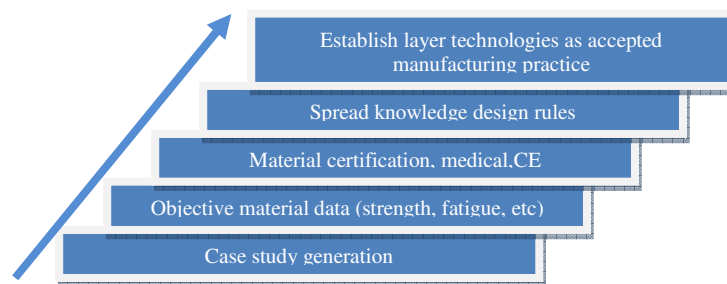
Wohlers(2006) illustrated the distribution of RM applications among typical activities (Figure 2.17) where the use of RP/RM technologies remains mostly as an aid for the prototyping and model making phases of design, however when compared to information from previous years, the use of RM for direct manufacture seems a growing tendency<sup>7</sup>.

<sup>7</sup> The same graph is Published on a yearly basis in the Wohlers Report which can be accessed on [www.wohlersassociates.com](http://www.wohlersassociates.com)



**Figure 2. 17** How companies are applying RM processes. Source: (Wohlers Associates, Inc., 2006)

The application of different RP/RM technologies has had a notable impact on the overall design process. According to Swift, Raines et al. (1999) this impact is translated to a cost reduction of around 40 -70 per cent and an overall time to market reduction of 90 percent. On a general perspective there are some steps the RM industry must go through in order to be an accepted technology, these begin with a growing quantity of case examples which may lead to the study, certification and performance assurance for both, process and materials (Figure 2.18).



**Figure 2. 18** Evolution and consolidation of RM source (Langer 2007)

From this general state of the art it is possible to oversee some tendencies of RM so a number of statements can be made:

- RM may be considered a still new method for fabrication
- Only few sectors have found advantages of using RM for niche markets
- The number of application examples remains limited since many companies see it as a competitive advantage and few cases are published or disclosed
- The range of applications of RM depends only on the adequacy to a given context coupled with the creativity of the designer.
- In order to get a broader “audience” and expand the possibilities and knowledge of additive processes it is necessary to adopt new means to convey the information to new designers and engineers.

### 2.8 The machinery and special equipment design sector

The aim of this research is to bring about a shift in the paradigm of conventional fabrication to start considering alternative means of fabrication especially in the sector of machinery and special purpose

equipment. This sector includes all industries dedicated to the production of machinery and appliances for low volume and special application for a wide variety of fields:

- Recreational equipment
- Metal mechanical equipment
- Motion control & mechatronics
- Food and beverages making
- Special purposes (exploration, research, etc.)
- Elevation and transport
- Materials handling/feeding, etc.

According to a recent Spanish study devoted to the Analysis of Special machinery and low series production sectors (García-Berro 2001) recent trends on equipment development are oriented to: modularity/multifunctional, new machine concepts, and robustness with higher added value. A special interest is shown on additive technologies referred in this industry as “non-conventional methods” especially for reverse engineering and low series production. In Spain only, the sector of equipment design represents roughly 1.7 per cent of the Gross Domestic Product (GDP) which means a 42.000 million Euros turnover (Panero 2007) and represents an strategic sector as it dictates the performance of many derivate industries (García-Berro 2001).

An domestic foresight study presented by Fundació OPTI (2008) predicts a division of RM technologies into: Conceptual models for office use and final production parts. The incorporation of RP / RM technologies as productive means for personalized micro-series is also expected accompanied by an improvement in the overall precision and material options. multi-material capabilities are also expected for the period 2005-2010, this shows a real interest on the application of Rapid Manufacturing technologies in this important sector. However it is interesting to note that many technological advances predicted for this industry are not expected to come from the application of additive technologies such as:

- Increase in the complexity and “aggressiveness” of design features
- Inclusion of embedded electronics for monitoring and maintenance
- Extra-hard materials with improved properties by means of sprayed coatings and post-processes
- Extensive use of KBE (Knowledge Based Engineering) for optimization of evolutionary designs

Regarding the last point, the panel of experts included in the same study (García-Berro 2001) foresees that in less than 5 years nearly 50 percent of industrial designers on this field will be using some KBE system that makes use of artificial intelligence and knowledge on concurrent product development in order to make better decisions. The main limitations rose from the use of KBE systems rely on the methodologies and knowledge capture techniques which comprise the main steps for their development.

### 2.9 Characteristics of the use of RM technologies

RM processes have important advantages but also drawbacks in need to be improved to achieve a wider acceptance. As stated by a number of previous works (Jacobs 1992; Fundación ASCAMM 1996; Freitag 2003; Hague, Mansour et al. 2004; ASERM 2006) there are well differentiated pros and cons in the usage of RM technologies which are presented in this section.

### 2.9.1 Pros of additive technologies

- Freedom of design. Due to the additive nature of the processes features such as internal shapes, undercuts, blind holes, and variable wall thickness are technically feasible compared to conventional processes.
- Draft angle projection is not an issue since direct RM doesn't make use of moulds. However for indirect processes such as Vacuum casting or resin moulds there's still a level of restrictions
- The elimination of moulds, dies and other tooling elements when using direct RM is an economical advantage
- RM is an enabling technology for the low volume, customised and niche market applications
- Customization for economical production of quantities of 1 is possible
- Its possible to make design changes when production has started without tooling to be modified
- Restrictions of the DFMA (design for manufacturing and assembly) are not necessarily imposed

### 2.9.2 Cons of additive technologies

- Machine precision is limited by a number of features such as laser diameter, internal temperature control, and layer thickness capability
- Low variety of materials. The number of available materials are still not comparable to established processes such as injection moulding or machining
- Lack of good material properties and high cost. Typical RM materials just mimic properties of conventional ones, however with the advent of the next generation of RM equipment, graded material end engineering compounds will be an option
- Final part features such as surface finish and density must be improved by post processing
- Part size is limited to the size of the machine work volume
- High cost of equipment and maintenance which translates to high part cost

Although the use of RM in the field of low volume manufacture of machinery and equipment has not been studied in depth, previous research shows that the use of additive manufacture techniques is not usually suitable for structural elements and the so called critical Parts (Freitag 2003). In the classification on parts, the department of defence of the United States defines parts according to the critical requirements to be fulfilled during its final application.

Class I parts include those where performance, quality and reliability are critical and the consequences of failure may be catastrophic. (Mills 2001) While the requirements for the qualification of Class I parts are extensive and expensive, less strict parts may be suitable to be produced by a given RM process. Class IV parts for instance comprise a lighter assurance testing since their failure does not mean an imminent danger and are therefore prone to be Rapid Manufactured.

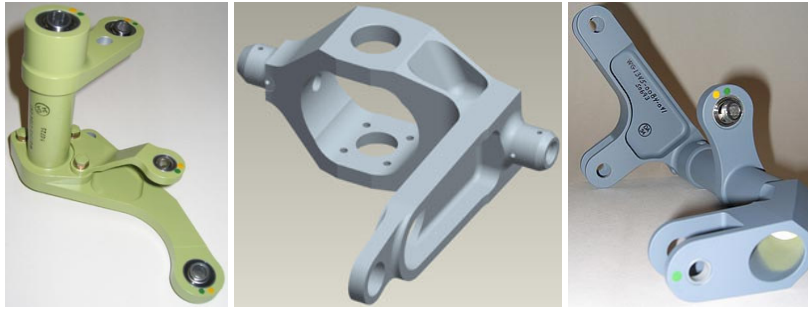


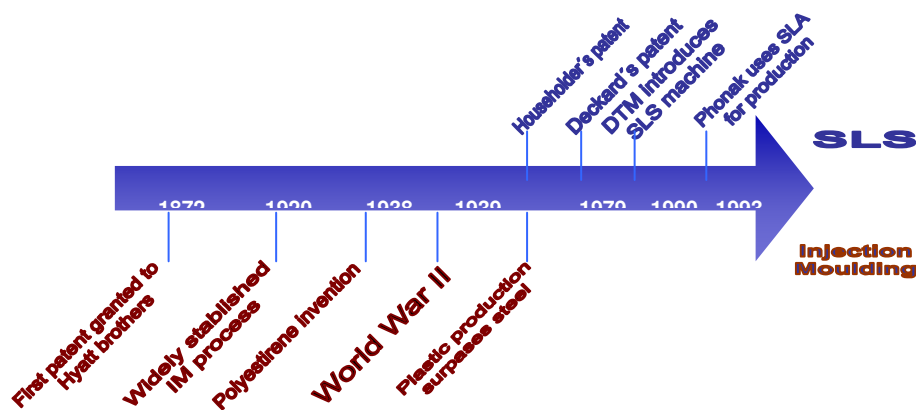
Figure 2. 19 A set of Class I critical parts for the aerospace and defence industries. Source <http://www.armedforces-int.com>

In the machinery and equipment design sector there is no such classification, it is possible however to infer from the initial set of product specifications (PDS) which parts are critical and which ones are not, and from those resulting, which of them are meant to be structural in order to identify suitable candidates to be rapid manufactured.

Besides its criticality and end use there are a number of factors that accompany a part in the search for a viable manufacturing route. Thus the concurrent approach undertaken in this research will deal with a number of criteria as follows:

- Part feasibility for RM
- Material properties suitability for the end use
- Process viability
- Economical assessment

While the pros and cons of rapid manufacturing can be stated and the balance with current technologies might be unfavourable it's important to offset their growth compared to other well established manufacturing methods which at the time of their introduction had similar disadvantages and limitations. This is the case of Injection Moulding (IM) as shown by Hopkinson and Dickens (2003) and Hopkinson, Hague et al. (2005), among the main restrictions imposed by this process during its introduction were: the lack of suitable materials for production, the lack of materials and a very low cost effectiveness. It took nearly 50 years from its introduction, to achieve the current performance and massive impact on product



development that IM has entailed (Figure 2.20).

Figure 2. 20 Comparison of the development of the Selective Laser Sintering process (SLS) and Injection Molding (IM) (Hopkinson, Hague et al. 2005)



In order to be aware of the potential benefits of RM it is important to address the knowledge and dissemination of these technologies so that their benefits can be embraced from the very early product development phases.

The RM selection tool presented in the next chapters is intended to capture expert's knowledge and technical information on RM technologies in order to convey this knowledge to potential users that may harness it, especially for products and designs which did not consider RM as a feasible manufacturing solution. Although strict and realistic, the system obviates some functional and productive drawbacks currently present on additive processes, so that it is possible to focus on their capabilities compared to conventional manufacturing alternatives.

### 2.10 Conclusion. The aim of this research

Based on the literature and general information discussed in this chapter, certain facts on RM can be stated:

- There is an important background and previous research on RP process systems, however still few works present RM as a final manufacturing alternative.
- Material properties are one of the major concerns conditioning a more widespread RM usage.
- Better and more comprehensive KBE systems are needed in order to disseminate key knowledge of additive processes so that new applications can appear in different or even unthinkable sectors.

The aim of this research is to move on the focus of current RP selection systems to end use Rapid Manufacturing. Although it is still a relatively new field, especially in terms of material properties, equipment capacity and productivity, recent industry examples have shown innovative applications that push RM capabilities to the limits of their capacity.

For this purpose three main criteria will be in depth covered

- Materials for RM
- current RM process capabilities
- Costing models and their integration into a methodology for overall RM feasibility verification.

The main scenario for this study is the design and development of machinery components and specialized equipment. Since it is possible to have access to the design portfolio, documentation and product data of a local machinery design centre (CDEI-UPC<sup>8</sup>), an important part of the emphasis and final applications will be addressed to this sector.

The resulting model for the selection and verification of the above criteria is meant to become an automated solution which might be capable of providing another field of application and generate a competitive advantage for the sector of machinery design.

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<sup>8</sup> Industrial Equipment Design Centre of the Technical University of Catalonia <http://www.cdei.upc.edu>

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# 3. Rapid Manufacturing characterization and general capabilities

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## *Abstract*

*This chapter starts the discussion on the need for Knowledge Based System (KBE) for capturing expert's knowledge. This knowledge should represent the main features of Rapid manufacturing processes however their parameters and features of interest must be recognized.*

*Firstly a general classification of RM is presented, followed by a description of the main capabilities and restrictions. This chapter concludes about the appropriateness of using such methods in spite of the several drawbacks they may entail.*

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### 3 Rapid Manufacturing characterization and general capabilities

#### 3.1 The problem of process selection

It is an accepted fact for designers that it is virtually impossible to memorize and be aware of the vast quantity of processes, materials, design factors, parameters, guidelines and their combination for an optimum design. It is also a generalized tendency to remain “attached” to the processing options that have provided the best results for previous design experiences (Boothroyd, Dewhurst et al. 1994). In other fields such as: art, architecture and similar disciplines, the adoption of a similar material or design configuration eventually becomes the “personal touch” of the designer, however in the field of engineering design and consumer products the adoption of new materials with diverse properties and the introduction of new designs with innovative features is a general rule. The constant evolution of design is actually fed by the continuous improvement of the available materials (Ashby 2005). This is also true for manufacturing processes whose evolution gives room for further improvements in the design itself.

However, the vast number of manufacturing options makes it difficult to track the appearance of new alternatives, and this is generally true for Rapid Manufacturing. While for the RM technical community it is easy to distinguish between the properties and capabilities of one technology or another, for a considerable amount of engineers, technicians and designers RM remains an unknown technology. Kruf (2008) makes an interesting affirmation to this respect which depicts a general picture of this scenario:

*“It is surprising that the use or even the existence of Rapid Manufacturing or Rapid prototyping is relatively unknown amongst engineers, designers or even students”*

It is not uncommon to find professionals of different manufacturing domains (e.g. metal sintering or machine shops) who have their first encounter with RM technologies almost “by chance” in random seminars or industry fairs. This lack of knowledge may also be attributed to a lack of lectures and courses on these techniques on the regular curriculum, therefore the development of Knowledge Based systems (KBE) applied to this technological domain can comprise a valuable reference not only for academia, but also for professionals in the fields of design and manufacturing.

Figure 3.1 and 3.2 show the survey results of a study made among industrial designers, about their knowledge and expertise on materials and manufacturing processes (Boothroyd, Dewhurst et al. 1994). Negative answers are presented in black, while a positive answer which indicates a sufficient knowledge of an individual process is shown in white.

Considering the responses on the white bars, the resulting graph may perfectly fit a normal distribution which could be interpreted as the concentration of a major expertise and knowledge on a smaller number of processes (injection moulding and metal extrusion), contrary to a lesser interest in more un-common processes. One of the possible consequences of this “knowledge gap” is the clear loss of opportunities for major manufacturing and design improvements due to the restricted number of processes and associated materials considered especially in the earlier stages of product design (Howard, 2002).

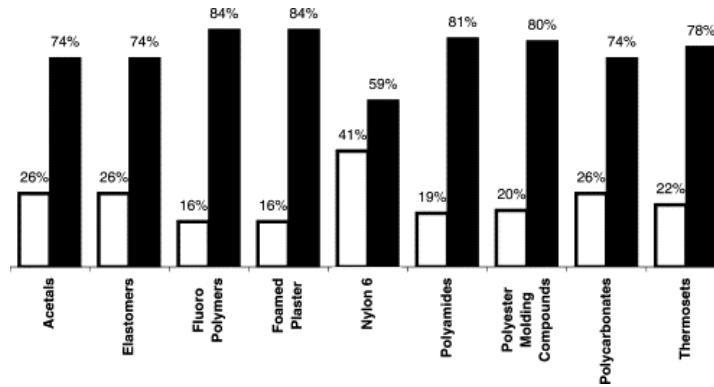


Figure 3. 1 Survey of designers' knowledge of manufacturing processes: (□) great deal/fair amount; (■) little or nothing (Boothroyd, Dewhurst et al. 1994)

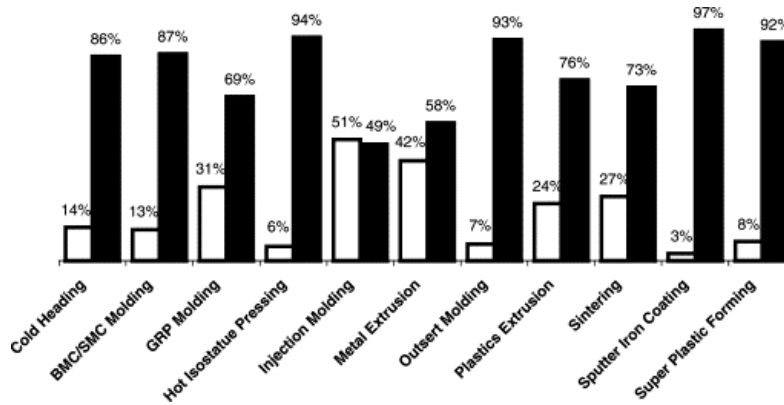


Figure 3. 2 Survey of designers' knowledge of polymer materials: (□) great deal/fair amount; (■) little or nothing (Boothroyd, Dewhurst et al. 1994)

This knowledge gap might be even increased due to the massive introduction of new and emerging processes such as RM which continues to enlarge the number of new technologies, improvements and system updates on a regular basis. However the development of KBE systems to aid during the design process and material selection phases may help on reducing this manufacturing knowledge gap.

A number of systems already exist which are being accepted specially by users from academia and to a lesser extend from industry. One of the most promising and commercially accepted is the “Cambridge Materials and Process selector” (GRANTA 2007) which is an example of a comprehensive materials database linked to process compatibility analysis, as it allows the selection of the proper alternative by deploying the screening method for processes or materials (Ashby 2005) where properties are filtered one after another until a few candidates are later selected by a graphical interface.

Covering the manufacturing and assembly issues of production, the software DFMA Dewhurst (2007) also incorporates a comprehensive materials database coupled with process compatibility and cost analysis, as the main focus is the concurrent costing analysis of assembly operations. Although it does not contain information on RM processes or materials it does illustrate a friendly way of approaching different costing factors usually hidden within the design such as: shape and complexity, aesthetics, tolerance factor, wall thickness, etc. A number of important academic contributions have been also made to the field of automated process and material selection tools. Dr. Guiachetti introduced the COMPASS system (Giachetti, 2004) which besides being a selection software, it studies some user-defined factors such as part complexity, functional features, processing and performance factors, in order to obtain the most suitable process option for a given part. One weakness of the system is the lack of costing information and material

data. Later on Wilson (2006) introduced a “feature recognition module” which linked to the Guiachetti's method provides an automated input directly from a CAD source. However it recognizes the necessity of using parametric and feature based CAD software in order to get the desired info for the system. Although some of the mentioned systems do include most commercial RP systems there's no a single systems designed for Rapid Manufacturing materials and process evaluation.

There is a strong tendency in the RM field for developing software automated tools as support for designers. Moreover it is considered that nearly 75% of industrial designers will be using some type of KBE tools as decision aids in the near future (Bernard 2003).

With the advent of Rapid Manufacturing techniques as real manufacture alternatives the range of materials, processes and design parameters are due to change and increase the number of options to manufacture our designs. Moreover the constant introduction of new materials, the advances in graded combinations and improvements on RM machine performance and capacity may lead RM to be an option no to be ruled out as easily as it currently is. Hence, the importance of a tool to aid in the during-design decisions for the selection of RM alternatives and if possible.

### 3.2 RM capabilities and general features

There is not yet a consensus for the classification of RM technologies, however different sources use the most convenient approach according to their purpose, namely: final applications, materials, cost, speed, size, etc.(Grimm 2004). Nevertheless two main approaches are more regularly used when trying to classify these technologies:

- classification by material
- classification by enabling technology

#### 3.2.1 RM classification by material type

Contrary to conventional manufacturing processes where for each process there is a wide variety of materials available for processing, Rapid Manufacturing is a very straightforward area for material / process selection since for each process there are a few dedicated material types (Fig 3.3).

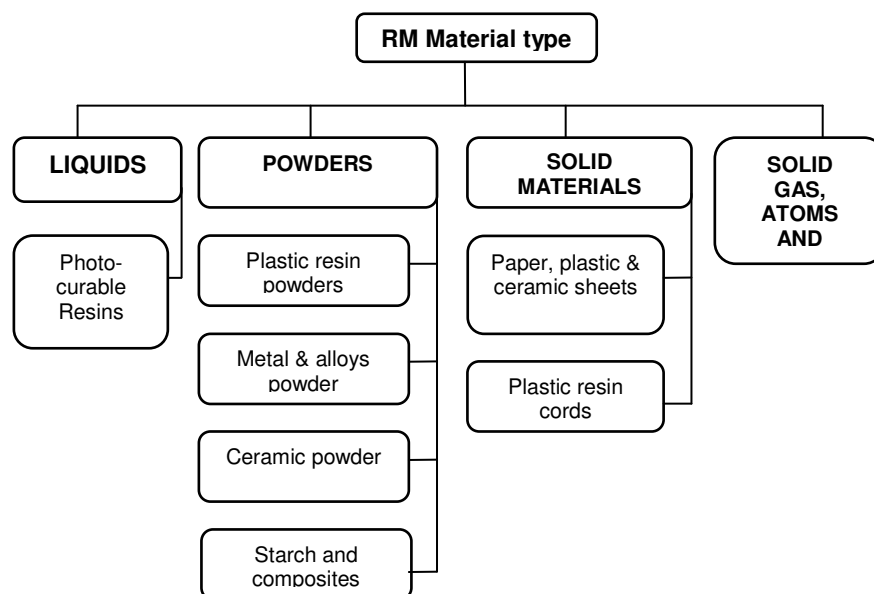


Figure 3. 3 A basic RP&M process classification based on material type



The above diagram may grow depending on the material typology considered by different authors. For instance while Steen (2003) normally includes three basic material states: Solid, Powder and liquid, Kouka (2006) also includes technologies under-development (or non-commercial academic developments) that rely on gas, vapour and other particle handling approaches. Figure 3.4 shows an extended sample graphic for RM process classification which extends according to the nature of the material and specific technology.

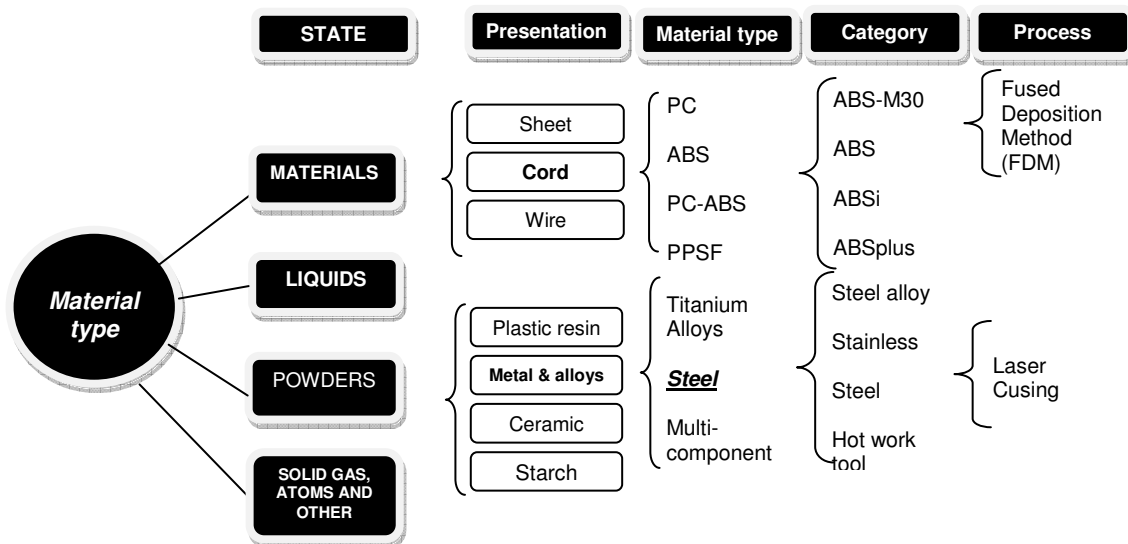


Figure 3. 4 The classification of RM processes by material type

Due to the complexity of the materials used in some existing and upcoming RM processes such as: graded materials, composites, bio and organic materials, the classification of RM technologies by the material used may lead to fuzzy results or uneasy classifications. Moreover the usual use of proprietary materials without much available information adds an element of risk to a materials based classification. An optimal material-based classification would rely on physical, mechanical, thermal and environmental properties; however the current shortage of such data in the RM field makes it necessary to focus just in basic material type categories.

### 3.2.2 RM classification by enabling technology

Another way to classifying RM processes is by defining their enabling technology; this approach starts by defining classes of processes. In the classification shown by Ashby (2004) RM technologies are considered as Primary process, this is, processes for creating shapes or near net shape parts<sup>1</sup>, the same as moulding, deformation or casting which later on the process must be subjected to secondary processes (to modify shapes or its properties) such as machining or heat treatment.

<sup>1</sup> “Near net shape” is a term coined to define the initial production of an item very close to the final shape, just before post-processes are applied

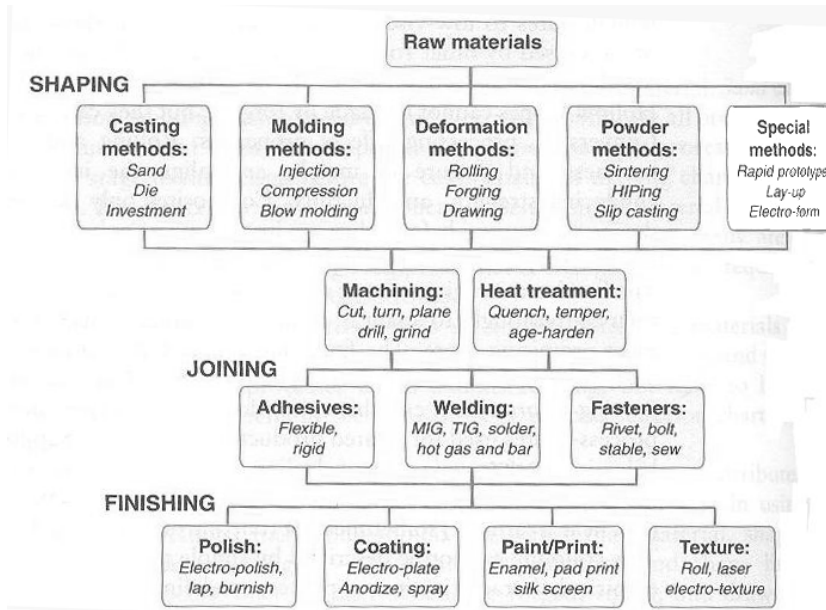


Figure 3.5 Process classification by process type

Secondary processes include joining methods (adhesives, welding, and fasteners) and Finishing, which is always a must for RM parts. Figure 3.6 shows a RM classification using the previous approach for current technologies which are extended to show the class, technology and goes further until ending in the specific process and its specifications.

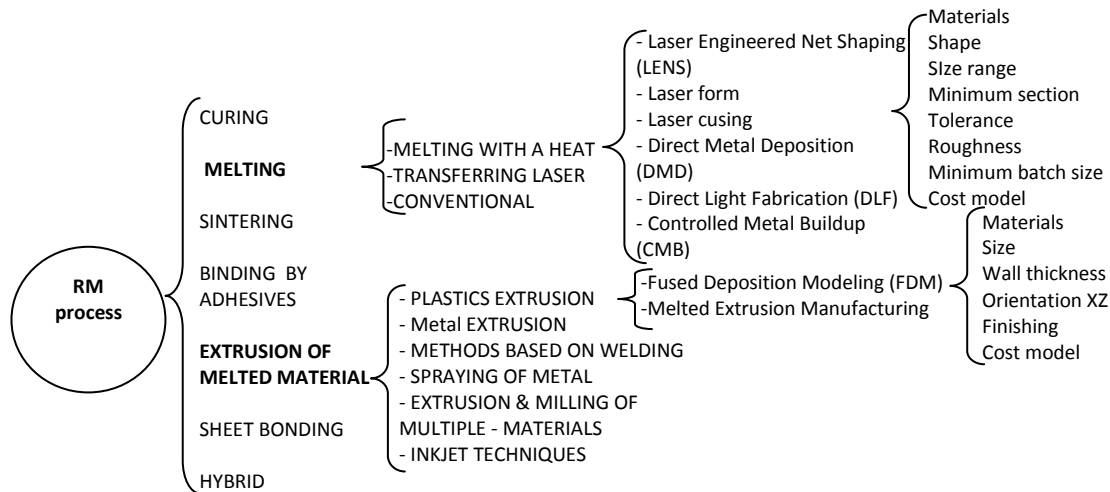


Figure 3.6 The Rapid Manufacturing classification by enabling technology

Kuoka (2006) makes a comprehensive RP& RM family tree based on their enabling technology. The classification is based on well defined principles as shown in the previous figure: Curing, melting, sintering, bonding and extrusion for instance, however with newer technologies appearing each year the classification is likely to rapidly change. Pham and Gault (1998) also presented a similar classification of RP technologies attending the physical principle of the process however most of the cited technologies are already discontinued.

The most common enabling technology used for RM processes is laser. There more than 25 different well established RM methods of which 70% are based on the application of lasers (Steen 2003). This makes it one of the most important parameters to be managed during RM process planning.

A full technology tree is included in Annex 1, showing RM processes currently on the market, as well as the technologies more recently introduced.

### 3.3 Requirements for process selection and RM parameters

From a DFMA approach, the selection of the most suitable process must fulfil two main requirements:

- Process compatibility with the desired material
- Compatibility of process capabilities with geometrical attributes, productive and cost requirements

For Ashby (2001) besides the geometric capability there are a number of attributes which must be assessed to assure process feasibility: material compatibility, shape, maximum part mass, section thickness, tolerances, surface roughness and cost, and the same is true for Rapid Manufacturing processes. According to different authors (Riba 2002; Wohlers 2006) the most important factors when evaluating RM processes for manufacturing are:

- Working Materials and its durability
- Process accuracy, speed and repeatability
- Overall costs: installation, maintenance, training

Without those factors the application of RM would not be feasible.

The list of working parameters for each RM process may be endless as they range from strictly technical ones, to those related to design, orientation and aesthetics. On the other hand while most of the processes studied herein are incremental or additive in nature they hold key differences between each other making it necessary to define the parameters which are common (or nearly equivalent) among the different technologies in order to allow for further comparisons and benchmarking.

Consider the scan and deposition speed parameter for the SLS process. It is provided as an aggregate of the scanning speed, laser power and beam diameter. On the other hand for the FDM process, the speed is an aggregate of different factors one of them being the speed at which the extruding nozzle moves over the 2D geometry. While “process speed” may be a simple and straightforward parameter to be determined by measures such as: square millimetres of dispensed material per second or a percentage of volume added per time unit, certain technologies bring forth a new set of evaluation criteria due to a different parameters configuration from one to another (Grimm 2002) Table 1 shows a few differences between the same definition of Speed between two processes: FDM and SLS.

**Table 3.1. Different factors affecting the FDM and SLS process**

<b>Some factors affecting speed for FDM</b>	<b>Some factors affecting speed for SLS</b>
<b>Layer thickness / tip size</b>	<b>Laser power / beam diameter</b>
<b>Air gaps between roads</b>	<b>Type of material to be sintered</b>
<b>Material feed rate</b>	<b>Layer thickness</b>
	<b>Hatching geometry</b>
	<b>Z height</b>
	<b>Thermal conditions</b>

While FDM is affected by fewer factors as shown in the table above, it is considered one of the slowest RM alternatives due to the low productivity specially for building multiple parts. On the other hand while SLS is one of the most parameter intensive processes is comparably faster. Therefore for a process selection software it must be possible to provide at least rough process comparisons from a reduced set of initial information, as it is needed when a product is still on the conceptual design stage Wilson (2006).

The following list discusses a number of important parameters and factors to be considered for the comparison and selection of RM processes.

### 3.3.1 Material compatibility

Usually in the form of a check-list, a material-process compatibility chart is useful as a first “screening” or discriminating factor when a new product is being designed. The following Table shows sample material-process compatibility for a number of RM materials and processes.

	Sand Casting	Die casting	Investment casting	Low pressure Die casting	Forging	Extrusion	Sheet forming	Powder methods	Electro-machining	Conventional machining	Injection molding	Blow molding	Rotational molding	Thermo forming	Polymer casting	Layer-up methods	3DP	DMLS	EBM	Envisiontec	FDM	Laser curing	LENS	Object	SLA	SLM	SLS
Metals, ferrous	•	•	•	•	•	•	•	•	•	•	•							•				•	•			•	•
Metals, non-ferrous	•	•	•	•	•	•	•	•	•	•								•	•			•	•			•	•
ceramics								•	•	•								•									•
Glasses										•	•	•															•
Elastomers										•	•		•	•	•						•				•	•	•
Thermoplastics										•	•	•	•	•	•						•			•	•		•
Thermosets										•	•		•	•	•									•	•		•
Polymer foams										•	•		•		•												•
Composites																•	•										•

Figure 3.7 Material-process compatibility chart

### 3.3.2 Shape and size

One of the main requirements for process selection is the ability or such process to generate the desired shape or its compatibility with a range of given geometric features. Shape and size parameters usually dominate on process selection and dictate the set of design guidelines to be followed in order to exploit the benefits of certain technology. Table 2 shows some shape attributes and complexity measures usually considered evaluating process capability.

Table 3.2. Shape attributes and complexity measure by different authors

Author	Shape attributes and feature classification	Measure of complexity
Guiachetti	1. Solid axial, 2. Hollow axial, 3. Rounded box, 4. Squared box, 5. Round flat, 6. Square flat, 7. Prismatic 8. Cone axial, 9. Tank	Is measured by describing part shape and its correspondent tooling cost. Uses a feature recognition approach for detecting internal and external undercuts, parting planes and shape class
Ashby	Prismatic (Circular Non-circular) Sheet (Flat, Dished) 3Dimensional (Solid, Hollow)	

Lucas method	Cylindrical Part: (Basic features only, repetitive features, Orthogonal, Simple curved features , Irregular ) * Prismatic Part (Basic features , repetitive features, Orthogonal, Simple curved, Irregular) * Flat or Thin-walled Section: (Basic features , Uniform section, non uniform wall thickness, Cup, cone, and box-type, contoured parts)	Provides a complexity factors depending on the selected process capability with the selected shape
Boothroyd	Depressions, Uniform wall, Uniform cross section, Axis of rotation, Regular cross section, captured cavity, enclosed cavity, No draft	Given in terms of process compatibility with geometrical features included in the piece

Process capability for shape features may be obtained from process-geometry tables available in general literature. However part complexity and shape issues do not seem to be a major driver for process selection in RM as it is for conventional processes. Due to the inherent ability of additive processes to generate almost any shape desirable, geometric classification is virtually unnecessary, unless it is used to compare the cost of an alternative route with conventional processes.

A grade of complexity however still exists for rapid manufacturing, though not expressed in the same terms. Mueller (2005) defines complexity for RM as: “the presence of hard to generate features such as undercuts, thin walls or very straight tolerances“. Usually, a highly complex geometry is associated to parts produced in low volumes due to the special procedures required to generate that shape, however since the additive nature of Rapid Prototyping technologies makes complexity a non-critical factor, less part analysis will be required.

Part size may also be a restricting factor since the work envelope of most RM processes continues to be relatively limited ranging from 250cm<sup>3</sup> to almost 1m<sup>3</sup>, however currently used materials give always the opportunity for welding, bonding or using a variety of joining options.

### 3.3.3 Tolerances

As final a manufacturing route, RM technologies may be considered as primary processes; therefore it is difficult to obtain tight tolerances. Some achievable tolerance levels are shown in the next figure. It is possible to notice how a number of RM methods appear to offer a tolerance range between 0.005in – 0.1in. This is clearly superior to the tolerance offered by other near-net shape process such as sand casting, which requires subsequent machining and polishing operations. However the tolerance levels for RM are variable and are directly influenced by surface roughness and other processing parameters (such as temperature and working environment).

### 3.3.4 Minimum section thickness

This feature decides whether a process may be considered suitable or not for a given part. For RM technologies the minimum wall thickness is partly determined by the minimum laser beam diameter (for laser technologies) or minimum nozzle diameter (for jetting mechanisms), though it will also depend on other factors such as grain size, material viscosity and thermal behaviour.

### 3.3.5 Surface roughness:

Usually available from textbooks and handbooks for a wide variety of processes, surface roughness is provided in units such as  $\mu\text{in}$  or Ra. It is defined on the basis of the ISO 4287 standard (ASM 1997) as the arithmetical mean of the deviations of the roughness profile from the central line along the measurement.

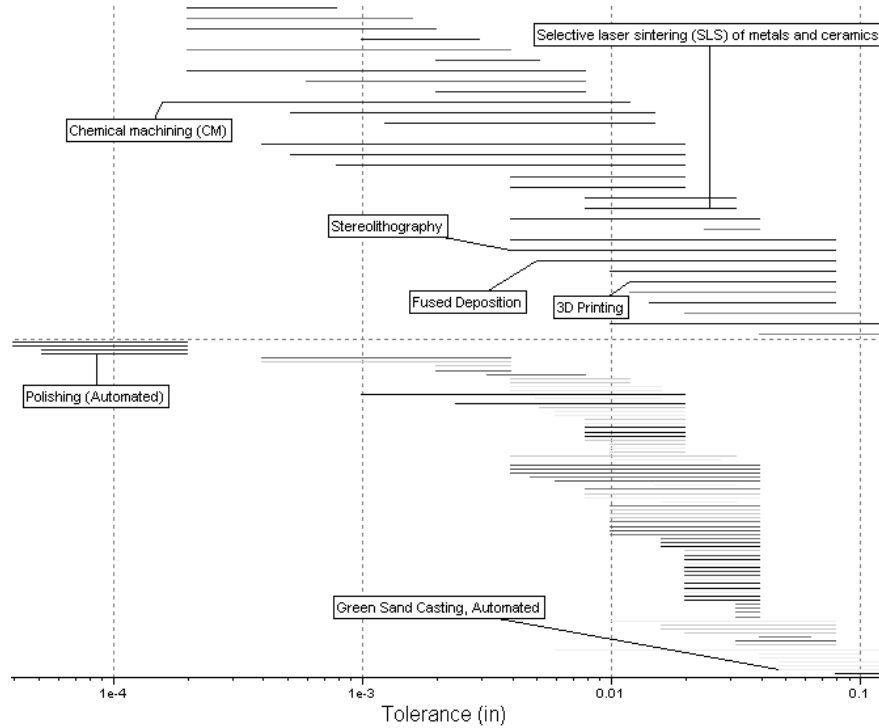


Figure 3. 8 Tolerance chart. Comparison of conventional and RM processes (CES Edupack, 2005)

Although there are several techniques for evaluating the surface roughness, one of the most commonly employed methods for characterising roughness involves assessment of surface roughness average by means of stylus instruments (Costa 2003).

Table 3.3 Conventional finishing levels (Costa 2003) Ashby, 2004)

Finishing $\mu\text{m Ra}$	Process
0,01	Lapping
0,1	Precision grind or lap
0,28	SLA
0,2 - 0,5	Precision grinding
0,5 - 2	Precision machining
4,5 - 7	Laser curing
2 -10	Machining
5,1 - 7,6	LENS
7,5 - 50	SLS
3 -100	Unfinished castings
9 - 11	DMLS
< 10	SLM
10 - 20	EBM

As the roughness levels vary with different manufacturing processes it can be improved by post-processing options such as sanding, grinding or the application of coatings which besides providing better finishing improve the superficial properties of the part. Table 3 shows different finishing levels for a set of processes compared to the approximate levels found for a group of RM technologies, all of them specified before post processing.

Other RM parameters affecting surface finish include: part orientation, layer thickness, extrusion diameter when available. Material type and its viscosity have been found to result in variable layer thickness during the build cycle, and other factors such as material recycling also cause surface alterations as the so called orange peel appearance (Levy 2003).

An additional consideration over surface resolution is the slice thickness defined at the pre-build stage, as this will have a direct effect on surface roughness (Reeves and Cobb 2007) this may be improved by increasing the number of surface facets. Support structures also affect final surface finish by leaving a series of witness marks on the component surface requiring additional post process finishing.

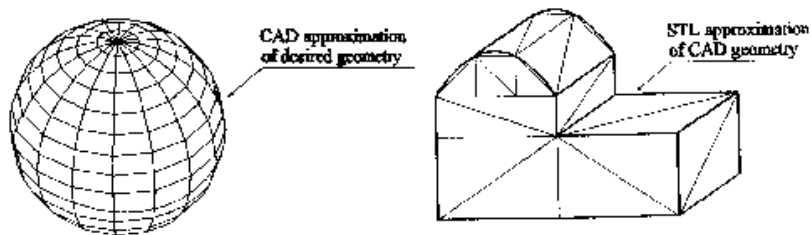


Figure 3.9 CAD approximation and STL tessellation

Since they're material dependent, different characteristics may be found for each process. Powder sintering techniques for instance leave a fuzzy dusty and porous surface, while those based on polymer curing have a smoother feel.



Figure 3.10 Surface finish for some RM processes: Left to right: SLS PA, SLS on Duraform Flex, and MJM

Annex 2 includes a comprehensive description of processes capabilities, main parameters and additional information collected from different sources during this research. It may be consulted for further information on specific parameters and values for the most common RM technologies.

### 3.4 Characteristics and surface appearance achieved with RM processes

#### 3.4.1 Stair-stepping

Due to the layer-wise fabrication style, RM exhibits a characteristic stepped surface which is less visible in technologies with better resolution, such as MJM or other resin deposition based, while in others like LOM or 3DP it is more evident due to the materials employed. Van Vaerenbergh (2008) developed a theoretical calculation of the size of the stairs on a sloping plane:

$$\text{Stair\_size} = \cos(\text{slope angle}) * \text{layer thickness}$$

Consequently the stair size can be reduced by decreasing the layer thickness or by increasing the slope angle (Figure 3.11-13).

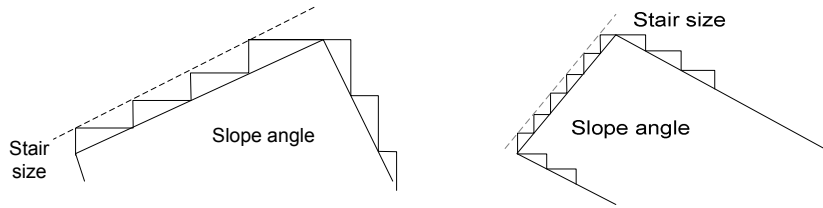


Figure 3.11 Slope angle and stair size for different part orientations

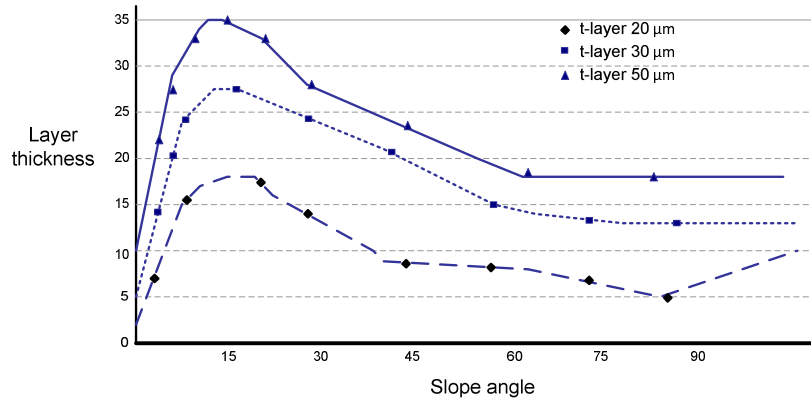


Figure 3.12 Average surface roughness of the SLM process as a function of Slope angle for different layer thicknesses (Van Vaerenbergh, 2008)



Figure 3.113 Stair-stepping appearance for some technologies: From left to right SLA, 3DP, inkjet, MJM

### 3.4.2 Support structures

Support structures are generally used when there is a need for sintering, depositing, curing, etc. a few layers of material over an area that has no previous material support. They are generated by some RM processes to prevent deformations and allow the construction of complex shapes; they make necessary a post-processing finishing operation. For metal processes they might be removed only through part machining, grinding or other material removal operations.



Figure 3.124 Some support structure types for RM. Left to right: SLA Quickcast, FDM Water soluble support, SLM with stainless steel

For some processes specially the metallic ones there is a number of problems that appear during the construction of thin layers and support structures:



- For laser enabled technologies, since the laser scans on loose powder instead of solid material, the thermal conductivity decreases and the temperature increases leading to unstable areas which may translate to high roughness or process failure during the powder deposition steps.
- “Stalactite patterns” are formed by the effect of gravity when a layer is solidified over loose powder, which at the end of the process is harmful for the overall surface quality.
- The effect called “curling” may appear during the process or during the cooling phase when a low-angle overhanging surface is not connected to both sides of the “bridge”.

**3.4.3 Other non conventional parameters to take into account in RM**

If a software tool for RM process comparison and selection is to be developed, the main parameters should be well defined and detected in all their elements. As in the example of the FDM and SLS processes, it is clear that for a more accurate comparison of speed and build time, a model that includes the mentioned parameters may be required.

**Table 3.4. Controllable and uncontrollable variables for the FDM process**

Some controllable variables	Some uncontrollable variables
Laser power	Scan speed
Preheating temperature	Material properties (unpredictable due to: ageing, recycling rates, etc.)
Nozzle speed	
Material	
Part density	

One common strategy for process comparison, modelling and characterization is design of experiments, usually applied to benchmark parts (Montgomery 1991) where the purpose is to determine controllable and uncontrollable factors that directly influence the process performance. For non-linear parameter relationships other methods such as Finite Element and neural network models have been also introduced (Boillat, Kolosov et al. 2004).

From a number of previous studies, experiments and conventional processes literature, a set of relevant parameters for RM processes have been identified in order to allow further comparisons between different technologies. Since each process might differ in key parameters, only those directly involved in cost, time estimation and quality assurance have been included. In addition only those that are common or nearly equivalent for each RM process have been considered since they usually differ in parameters such as laser source, optics, powder deposition, scanning equipment and environment control system, however Process parameters, such as layer thickness, laser power and scanning strategy are optimized for each process depending on the applied binding mechanism, and chosen powder material (Kruth, 2005).

However optimizing a process with respect to a large number of operating parameters is a complex, time consuming, tedious and sometimes risky task (Levy, 2003). Besides this approach is usually based on trial and error which might result prohibitive when experimenting with certain RM processes. An alternative practice to DOE is the manufacturing of benchmark parts.

On the other hand as stated by Ruffo (2006) it might be incorrect to estimate a micro- variable (i.e. laser speed, diameter) when there are other micro-variables destroying the precision of the estimation. A reduced complexity model has been recently proposed for process comparison from a set of simple geometrical drivers namely height, volume, and bounding-box volume. While not a universal method, since

it has been exclusively applied to the SLS process it shows a tendency to simplify calculations in order to make possible comparison with between different technologies.

#### 3.5 Conclusion

The common problem of process/material selection has been introduced in this chapter, along with the tendency to develop KBE to overcome the shortage of sufficient knowledge in certain manufacturing domains. The description of different Computer Aided Systems for RM will be subject for the following chapter, however it is the intention of this section to argument how such systems may be helpful to store process data, and present it in the form of knowledge depending on the capabilities required by the user.

It is expected in the long term, when Rapid Manufacturing reaches the level of other widely accepted processes, that more and more KBE systems will include and absorb RM knowledge in order to add it to its knowledge base. However at the meanwhile, there are not enough tools to support the incipient attempts to apply RM for production.

Some of the difficulties for performing a reliable comparison between different RM technologies may be their enabling technology and the different materials they are capable to process. While it may not be appropriate to compare two options based on single parameters such as speed (as curing a photo-curable resin is a different process that sintering a polymer), it may be more appropriate to perform a comparison based on an aggregate characteristics: surface roughness, minimum feature detail, tolerances, etc. therefore it is necessary to characterize all involved parameters; for instance for surface roughness it is important to know: layer thickness, laser and scan parameters, slope angle, scan strategy, etc.

There are also some non-conventional implications of RM processes such as the stair stepping effect which is inherent to all layered methods, and the need for support structures which are necessary especially for metal-based technologies. There few exceptions such as SLS where each new layer is fully supported by the powder bed. Currently the design of support structures is semi-automated, it means that specialized software of the proprietary machine software may be capable of detecting the geometries in need for supports, however as this is not always the best solution, the expertise of the designer counts when deciding the part orientation, material, and build strategy, comprising another reason for the need of adequate KBE systems.

This chapter presented generic aspects and capabilities of RM that must be considered prior to proceeding to establish a comparison between conventional manufacturing methods. The following chapter starts the development of an automated method for process selection which will be continued until the final chapter of case studies.

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# 4. Outlining the Rapid Manufacturing advice system: RMADS

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## *Abstract*

*This chapter presents an overview of the RMADS system, presenting the whole application as an aggregate of individual modules that must be developed. The main modules are: General design requirements, Materials and Cost calculation, however as they are intended to work in an independent manner the functions and implications are presented, relying on flow charts and schemes.*

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## 4. Outlining the Rapid Manufacturing advice system: RMADS

### 4.1 Introduction

In this section the development of the architecture of the Rapid Manufacturing Advice System (RMADS) is discussed. It is intended to recommend the most appropriate route for creating a final fully functional part. Its main difference with previous selection systems consist in the concurrent evaluation of several manufacturing techniques from a set of initial user defined input parameters. The final goal is not the selection of prototyping processes, but the assessment of RM alternatives as feasible manufacturing options for end-use parts. This requires a series of steps in order to assure the feasibility of the system's proposal.

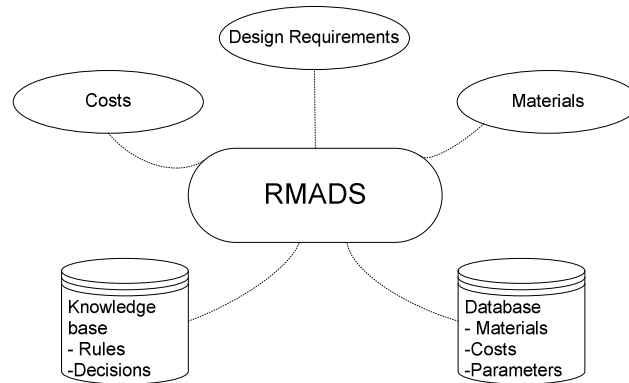


Figure 4. 1 The RMADS structure

### 4.2 The system's architecture

The RMADS architecture is comprised of 3 modules working together with data extracted from two main databases to support the decision making task (Figure 4.1). The model is based on an object-oriented methodology (Masood and Soo 2002) i.e. it is capable of working with independent modulus performing event-driven calculations according to user selection. The following models comprise the whole system:

#### 4.2.1 Module 1. General design requirements

Starting from a series of parameters in 4 groups: geometry, appearance, functional and mechanical requirements, the main function of this module is to carry out the screening process to eliminate those alternatives which do not satisfy initial design requirements. Their internal system is comprised by two distinct engines: a fuzzy logic base inference system, and an expert system designed with rules in a selection tree. The internal aspects will be detailed in the following chapter. The general architecture of this system follows the scheme shown in Figure 4.2.

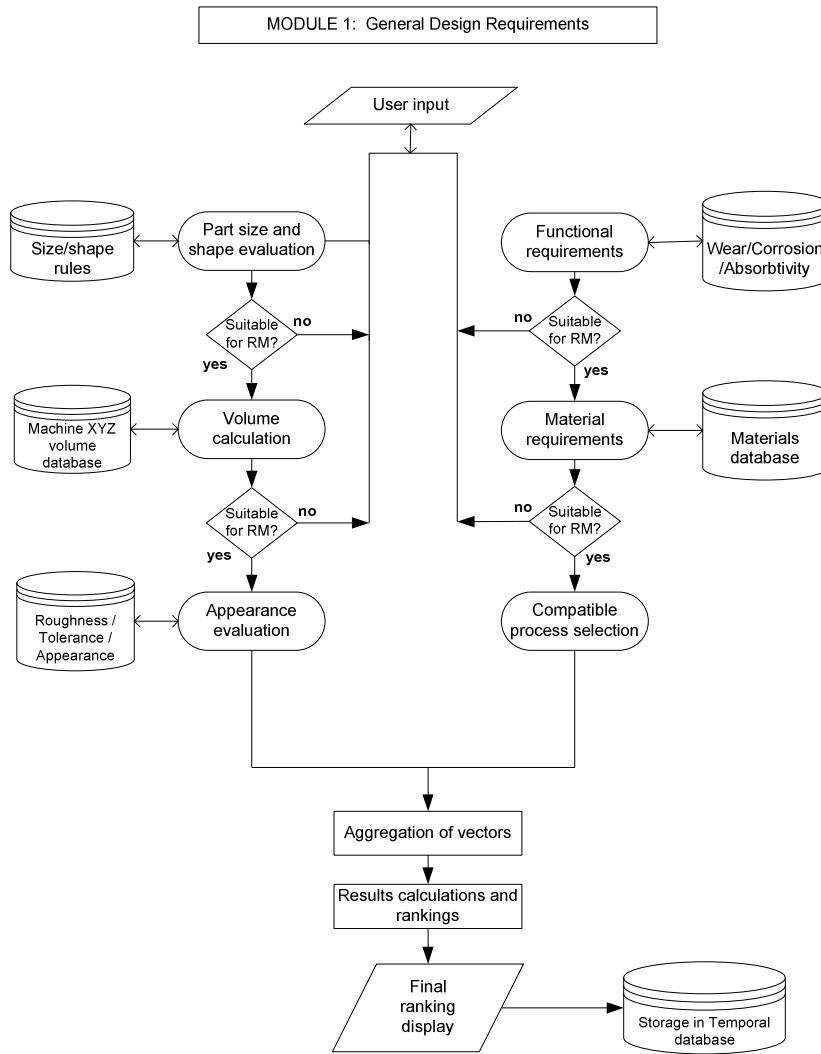


Figure 4. 2 Scheme of module 1

#### 4.2.2 Module 2- Economic assessment

Once a number of RM processes have successfully passed the previous stage, cost assessment is undertaken. This module exploits up to date Artificial Intelligence knowledge on Artificial Neural Networks (ANN) for cost estimation in addition to previously developed parametric models (Ruffo, Tuck et al. 2006; Wilson 2006) to get an approximate part cost for each additive technology.

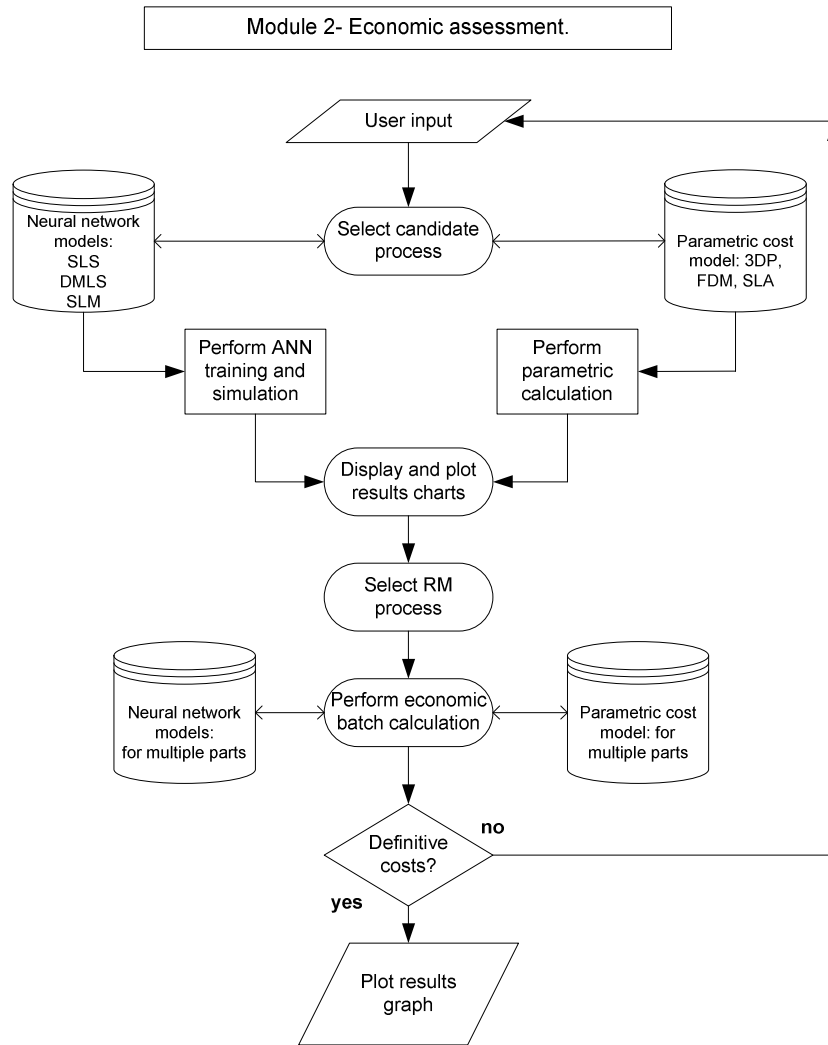


Figure 4. 3 Scheme of module 2

#### 4.2.3 Module 3. Materials properties

This module is comprised of an expert system linked to relational databases in order to show feasible materials for the intended end use depending on the properties selected by the user. On the one hand this module contains an expert system which stores a series of user-selected rules for the screening of material candidates. And on the other hand the system also displays graphs based on material parameters so that the final selection is twofold, graphical and rule-based.



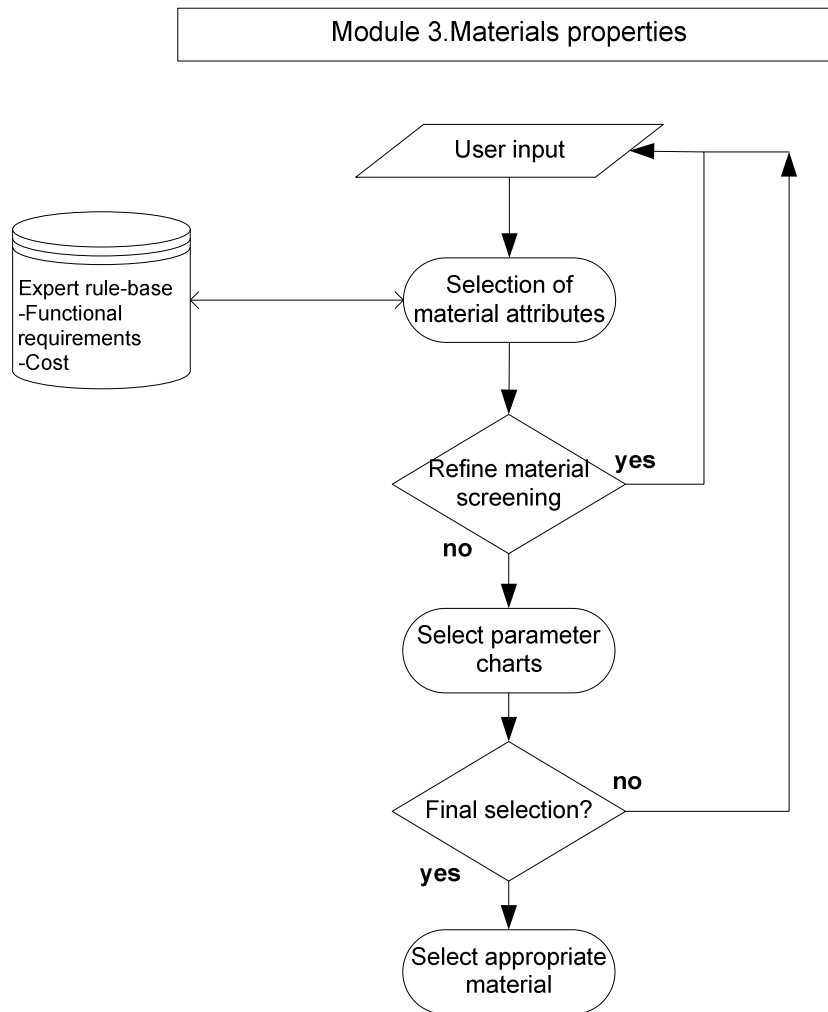


Figure 4. 4 Scheme of module 3

### Conclusions

Before describing in depth the RMADS system it is important to graphically describe its different elements. This helps illustrating the information flow and user interaction so that their implications are clear. In the previous graphs it is possible to outline the basic elements of the RMADS system which comprise:

- User interface
- Relational databases
- Expert rule systems
- Fuzzy logic-based decision systems
- Artificial Neural Networks for estimation
- Parametric models for estimation

It is expected that all these elements can be assembled so that the result becomes a flexible concurrent system for the selection of the more appropriate RM technology for a given task. The detailed development of these elements is undertaken in the following chapters.

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# 5. General Design requirements

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## *Abstract*

*This is the core chapter of this thesis as it makes, in a first place, a comprehensive review on the state of the art of Rapid Prototyping selectors. Afterwards it starts with the development of the main module of the RMADS system: the "General Requirements module". This section presents the detailed calculation and logic behind the system, ending with the application of a sample case for illustrating the use of the system. Throughout the chapter it is possible to identify some of the Artificial Intelligence tools utilized in this research, that is the case of: Expert systems for decision making and Fuzzy Logic for the conversion of Linguistic terms to fuzzy numbers, in order to perform the appropriate calculations.*

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### 5. General Design requirements

#### 5.1 Introduction

During the product development process, it is important to consider manufacturing issues since the earlier stages in order to achieve reductions on time, costs and improve the quality. According to Ullman (1997) although design represents a rough 5% of the final product cost, upwards 70% of total cost is determined in this stage. However an early consideration of manufacturing alternatives during the design stages might bring associated drawbacks. For instance depending on the designer's knowledge on manufacturing processes and materials, available options might be inappropriately narrowed, thus guiding to a non-optimum solution. This selection task during preliminary engineering design is characterized by qualitative descriptions of requirements, imprecise data and complex relationships (Giachetti, 1998).

The high number of materials to be evaluated and their combination with different suitable processes leads the designer to rely on his personal experience and apply the options that have provided the most satisfactory results in the past. This gap between the designer's knowledge and available manufacturing technologies might be even increased with the massive introduction of new processes especially in the last decade when most of the currently used additive technologies were launched (Grimm, 2004).

A number of manufacturing decision software is available to help reducing this manufacturing knowledge gap. The Cambridge Materials and process selection (GRANTA, 2007) is an example of a comprehensive materials database linked to process compatibility and capacity. Also, addressing the manufacturing and assembly issues of production the software DFMA (Dewhurst, 2007) also incorporates a comprehensive materials database coupled with process compatibility and cost analysis although it focuses in the concurrent costing for DFM and assembly. (Dieter, 2000), (Shercliff and Lovatt, 2001), besides other specialized sources (ASM, 1997) contain a more detailed compilation of computer-aided selection for further reading.

Rapid manufacturing technologies are derived from Rapid Prototyping (RP) processes that appeared in the early 90's (Jacobs, 1992). Their principle of additive fabrication to construct complete parts by depositing thin layers of material has grown into a set of technologies suitable for the manufacture of end use products depending on the material, parameters selected and the function to be performed.

Although it has been claimed that RM may cut product development cost by 70% and time to market by 90 % (Waterman, 1991) there are currently no systems available for the assessment of RM technologies as potential manufacturing routes. However there is relevant work on the selection of processes solely devoted to prototyping purposes. These are presented in the next section.

##### 5.1.1 Previous attempts for RP selection

Rapid prototyping refers to those technologies capable of producing prototypes directly from a CAD source, via layer-wise deposition (Bibb et al., 1999, Masood and Al-Alawi, 2002). The selection of the optimum RP process usually depends on factors such as build envelope, accuracy, material, build speed and other machine-related parameters. With around 22 manufacturers marketing between 40 and 60 models of RP machines (Wohlens, 2006), the development of computer-based selection systems has been a recurrent topic in RP related literature (Masood and Al-Alawi, 2002).

Probably the first attempt to develop a computer based program for RP selection was made by Dr. Hornberger (1993) at Santa Clara University whose system was mainly used as an academic aid for process selection among those RP processes available by 1993. The program provides general information about rapid prototyping, some machine specifications, a simple process comparison and suggestions for process selection.

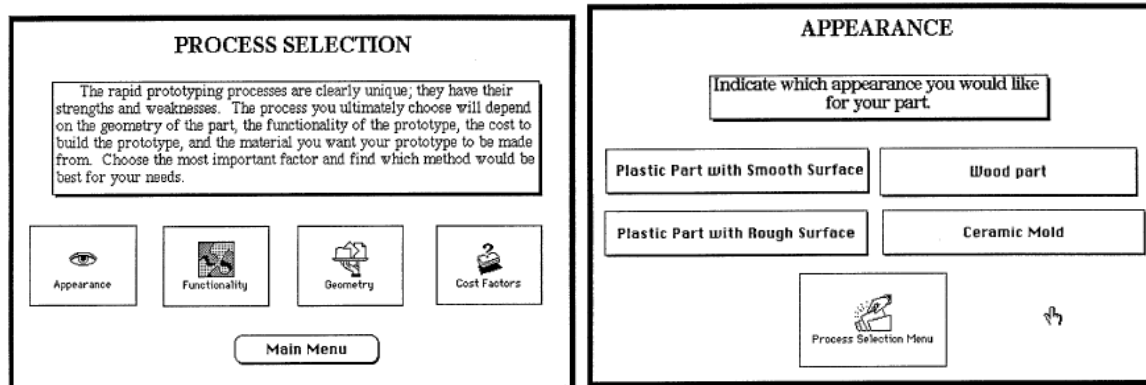


Figure 5.1 The Santa Clara Univ. program. a) Main process selection screen b) Sub menu for the option Appearance

Other systems based on relational databases were introduced by Muller (1996) and Campbell & Bernie (1996). The former was rather focused on finding the best materials- process combination expressed in percentages by applying the so called "Benefit Value Analysis". *An example of the evaluation is given as: "first place, 83% of requirement degree, for the machine ABC with material XYZ"* (Muller, 1996). Later research from this same institution focused on Rapid Tooling techniques within the complete RP process chain. Campbell (1996) introduced the RP process capabilities database, which through the use of relational databases was intended to find the best match between RP process capabilities and part features (thin walls, primary shape, holes, bosses, chamfers and other key features). However the comprehensive task of building a database that contains the values for every feature built using every RP system, would make the system unreachable in terms of cost to the casual user such as small companies (Bibb et al., 1999).

Later on Phillipson (1997b) from Arizona State University introduced the RP Adviser also based on relational databases applying Ms Access® (Microsoft, 2005). It made use of mathematical relations and multi-criteria optimization to find the best alternative, besides deploying interviews with experts to check the system's effectiveness. A more comprehensive version of this selector was introduced by Phillipson (1997a) who introduced a build-time calculation model, that relays on basic 'scan speed' formulas of for different RP processes. It is also one of the first selection models to include a cost calculation method which allowed the user to define certain parameters such as material, labour and overhead costs.

The screenshot shows three input boxes for the RP Adviser. The first box, 'Dimensional Accuracy', has a 'General' radio button selected and three buttons for tolerance ranges: '+/- 0.02 in.', '+/- 0.005 in.', and '+/- 0.003 in.'. Below it is a 'Specific' radio button and a text input field containing '0.0050 +/- in.'. The second box, 'Surface Finish', also has a 'General' radio button selected and three buttons for surface finish values: '500 micro in.', '32 micro in.', and '1 micro in.'. Below it is a 'Specific' radio button and a text input field containing '1.00 micro in.'. The third box, 'Part Complexity', has three buttons: 'Simple', 'Medium', and 'Complex'.

Figure 5.2 Screenshot of the RP Adviser input boxes

Knowledge-based expert systems for RP selection were later introduced by Bibb et al. (1999), Bernard (2003), Masood and Soo (2002), the later from the Industrial Research Institute Swinburne (IRIS), Australia. This software was partially based on data gathered from users survey on selection criteria and their own applications to feed the base of knowledge, however, in despite of its comprehensive databases the system still lacks of cost, materials and build time information since it's intended for equipment selection for purchase.

The figure shows two screenshots from the IRIS RP selection system. The left screenshot is titled 'IRIS\_Quick Selection' and 'QUICK SELECTION METHOD'. It contains several dropdown menus for input: 'Country', 'Price (US\$)', 'Accuracy XY (mm)', 'Envelope Width (mm)', 'Envelope Depth (mm)', 'Envelope Height (mm)', and 'Build Material'. The right screenshot is titled 'IRIS\_Quick Selection Result' and 'Quick Selection Result'. It shows the 'Number of Recommended Systems' as 6. Under 'Recommend System NO. 1', it lists details for 'RP System: Actua-2100', 'Technology: InkJet Printing', 'Price (US\$): \$5000', 'Accuracy (XY) (mm): 0.25', and 'Accuracy (Z) (mm): 0.25'. It also lists 'Material Used' as 'click to see the Material Used'. A table shows dimensions: Envelope Height (250 mm), Envelope Depth (250 mm), Envelope Width (250 mm), Machine Height (1120 mm), Machine Depth (760 mm), and Machine Width (1370 mm). Other details include 'Vendor: 3D Systems, Inc.', 'Vendor Address: 26081 Avenue Hall, Valencia, CA 91355', 'Country: USA', 'Build Thickness minimum (mm): 1', 'MultiPart Building: Yes', 'Build Speed (cm3/hr): 14', and 'Machine Weight (kg): 318'. An image of the Actua-2100 printer is shown on the right.

Figure 5.3 Data input screen for the IRIS RP selection system, and the resulting screen

Lan (2005) introduced the Fuzzy synthetic evaluation method for the treatment of qualitative and quantitative data for comparison and weighting purposes. It splits criteria factors into: Technology, Geometry, Performance, Economy and Productivity considering a couple of factors for each process in order to compare them. The merit of the system relies in the use for the first time of linguistic terms in order to handle imprecise data by the use of fuzzy logic. Nevertheless the final result provides a RP ranking process similar to previous systems which lack of further information on costs, materials or build time.

## Rapid Prototyping System Selector

Technological Features	
dimension accuracy	[0.15-0.2] mm
surface roughness	[3.2-6.3]
Geometric Features	
maximum length of prototype	[240] mm
maximum width of prototype	[100] mm
maximum height of prototype	[150] mm
geometrical complexity	[medium]
solid	<input type="radio"/> Yes <input checked="" type="radio"/> No
minimum wall thickness	[0.3] mm
Prototype Performance	
mechanical behavior	[medium]
heat resistance	[medium]
Prototype Purpose	
use of model	[master pattern]
master pattern of rapid tooling	[investment casting]
Economy	
running cost	[low]
post-processing cost	[low]
material cost	[low]
equipment cost	[low]
Productivity	
scan speed	[high]
overhead time	[less]
post-processing time	[less]
Other Requirements	
prototype of material	[wax]
number of pieces	[10]
Remark	
<input type="text"/>	
Xi'an Jiaotong University Web-based RP System Selector 2003 Copyright Reserved	
<input type="button" value="Submit"/> <input type="button" value="Reset"/>	


Figure 5.4 Main data input screen for the RP selector designed by Lan et.al. (2005)

Mahesh (2005) addressed an integrated rapid prototyping decision-making system (IRPDMS) based on fuzzy decision and benchmarking for selecting appropriate rapid prototyping and manufacturing (RP&M) processes. Data sets captured from benchmarking different RP&M processes are used in decision-making. The proposed IRPDMS provides decision support while interacting with an earlier developed benchmark database. The disadvantage of the systems is that it doesn't adopt a generic approach. It's based on a single part benchmarking for comparing five well know processes. Hence the task of measuring multiple parts and feeding databases doesn't seem to be the right choice for developing a selection system unless it is for a specific in-house application.



**RP&M BENCHMARKING Decision Support Systems**

Based on your Prototype, make the appropriate selections from below and then click the Suggest name button.

<b>General Geometrical Accuracy</b>	X-axis	<input type="radio"/> Low (GA > 0.5 mm) <input type="radio"/> Medium (0.5 < GA < 0.2 mm) <input checked="" type="radio"/> High (GA < 0.1mm)	
	Y-axis	<input type="radio"/> Low (GA > 0.5 mm) <input type="radio"/> Medium (0.5 < GA < 0.2 mm) <input checked="" type="radio"/> High (GA < 0.1mm)	
	Z-axis	<input type="radio"/> Low (GA > 0.5 mm) <input type="radio"/> Medium (0.5 < GA < 0.2 mm) <input checked="" type="radio"/> High (GA < 0.1mm)	
<b>Desired Surface Roughness, Ra (in µm)</b>	<input checked="" type="radio"/> Fine (Ra < 5 µm) <input type="radio"/> Rough (50µm < Ra < 5 µm) <input type="radio"/> Coarse (Ra > 50 µm)		
<b>Mechanical Properties</b>	<input checked="" type="checkbox"/> No Preference		
	Tensile Strength	<input type="radio"/> Poor <input type="radio"/> Medium <input type="radio"/> Good	
	Cast	<input type="radio"/> Poor <input type="radio"/> Medium <input type="radio"/> Good	
	Shear strength	<input type="radio"/> Poor <input type="radio"/> Medium <input type="radio"/> Good	
	Compressive	<input type="radio"/> Poor <input type="radio"/> Medium <input type="radio"/> Good	
	Creep	<input type="radio"/> Poor <input type="radio"/> Medium <input type="radio"/> Good	
<b>Individual Geometries in the prototype</b>	<input type="checkbox"/> No preference		
			
	Holes	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input checked="" type="radio"/> Most Accurate	
	Cylinders	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input type="radio"/> Most Accurate	
	Squares	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input type="radio"/> Most Accurate	
	Corners	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input type="radio"/> Most Accurate	
	Spheres	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input type="radio"/> Most Accurate	
	Slots	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input checked="" type="radio"/> Most Accurate	
Brackets	<input type="radio"/> Less Accurate <input type="radio"/> Medium <input type="radio"/> Most Accurate		
<b>Minute features</b>	Thin walls	<input type="radio"/> Thin wall <= 0.5mm wall thickness <input type="radio"/> 0.5 < Thin walls <= 1mm wall thickness <input type="radio"/> Thin walls > 1mm wall thickness <input type="radio"/> Thin cylinders <= 0.5mm diameter <input type="radio"/> 0.5 < Thin cylinders <= 1mm diameter <input type="radio"/> Thin cylinders > 1mm diameter <input type="radio"/> Smallholes <= 0.5mm diameter <input type="radio"/> 0.5 < Smallholes <= 1mm diameter <input type="radio"/> Smallholes > 1mm diameter <input type="radio"/> Simple freeform features <input type="radio"/> Complex freeform feature	
	Thin cylinders		
	Small holes		
	Freeform		
	<b>Mechanical Features</b>	Fillets	<input type="radio"/> Select if the model has fillets
		Chamfers	<input type="radio"/> Select if the model has chamfers
Blends		<input checked="" type="radio"/> Select if the model has blends	

Suggest name    Reset

Figure 5. 5 Screen capture of the system developed by Mahesh (2005)

The Helsinki University of Technology (2002) also launched its RP-selector based on a series of 12 questions requiring user input on part accuracy, layer thickness, geometric features, requirements, etc. There is also a scaling factor to be selected for each question which makes the system hard to complete for a single analysis. The system is completely devoted to prototyping and also includes some options of Rapid Tooling as can be seen in Figure 5.5. It also makes use of linguistic variables to describe the user options however there is not quantitative information required, therefore cost issues are not included within the system.

<b>6. Model will be used as a master in secondary process:</b>	<input type="radio"/> RTV <input type="radio"/> Investment Casting <input type="radio"/> Die Casting <input type="radio"/> Other <input checked="" type="radio"/> None
<i>Weight for this question:</i>	<input type="radio"/> Insignificant <input type="radio"/> Less <input checked="" type="radio"/> Average <input type="radio"/> More <input type="radio"/> Important
<b>7. Use of Model:</b>	<input checked="" type="radio"/> Form, Fit & Function <input type="radio"/> Concept <input type="radio"/> Tooling <input type="radio"/> Other
<i>Weight for this question:</i>	<input type="radio"/> Insignificant <input type="radio"/> Less <input checked="" type="radio"/> Average <input type="radio"/> More <input type="radio"/> Important
<b>8. Model features: Wall thickness</b>	<input type="radio"/> Very Thin <input type="radio"/> Thinner <input checked="" type="radio"/> Nominal <input type="radio"/> Thicker <input type="radio"/> Thick
<i>Weight for this question:</i>	<input type="radio"/> Insignificant <input type="radio"/> Less <input checked="" type="radio"/> Average <input type="radio"/> More <input type="radio"/> Important
<b>9. Model features: Mass</b>	<input type="radio"/> Light <input type="radio"/> Less <input checked="" type="radio"/> Nominal <input type="radio"/> More <input type="radio"/> Massive
<i>Weight for this question:</i>	<input type="radio"/> Insignificant <input type="radio"/> Less <input checked="" type="radio"/> Average <input type="radio"/> More <input type="radio"/> Important
<b>10. How much are you willing to pay for the model?</b>	<input type="radio"/> Not much <input type="radio"/> Less <input checked="" type="radio"/> Nominal <input type="radio"/> More <input type="radio"/> A Lot
<i>Weight for this question:</i>	<input type="radio"/> Insignificant <input type="radio"/> Less <input checked="" type="radio"/> Average <input type="radio"/> More <input type="radio"/> Important

Figure 5.6 Screen capture of the web based system available from HUT (2002)

Another web-based RP selection tool was launched by the Industrial Research and Development Corporation (Ivf Sweden, 2005), which through only three questions: material/function, quantity, end use requirements, presents a window containing series of recommended processes and their additional information. A definitive ranking is not included however this is one of the first programs to include Rapid Tooling as an option.

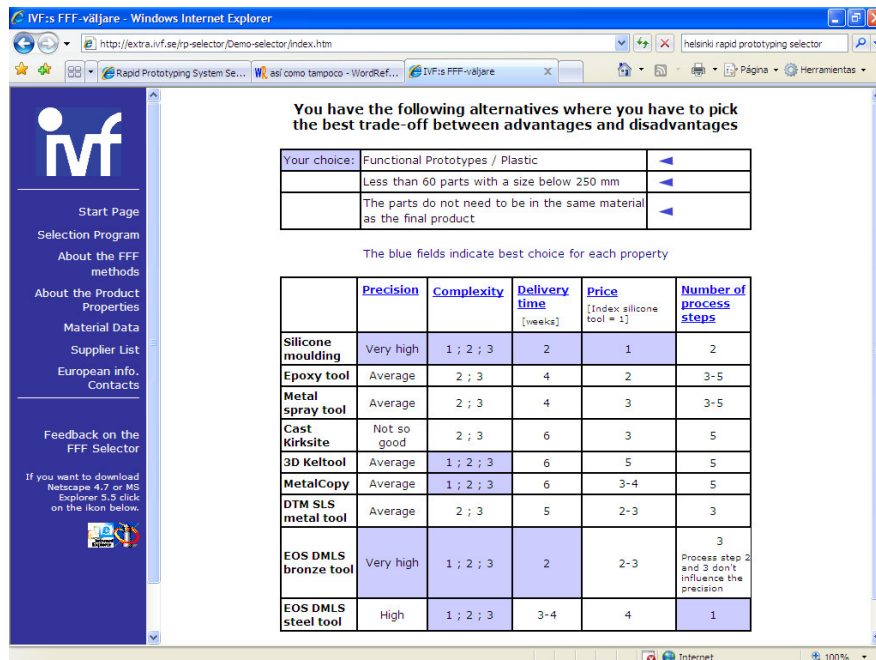


Figure 5.7 Screen capture of the results screen from the ivf selector

Following the web based approach the Spanish Rapid Manufacturing Association (ASERM, 2006) recently launched a RP selector which clearly distinguishes between two options: the use of additive processes for prototype construction and the use of rapid tooling methods for final parts and pre-series. However the system still lacks of costing, materials information and a more comprehensive input since it's based basically in generic data regarding the part's build volume, overall tolerance and type of material.

A comprehensive comparison chart for the RP selection systems herein described is provided in Annex 5.1 so that the main implications and detailed input parameters, selection criteria and output information are defined in detail. Although these methods contain a suitable logic for a RP process selection, they may not comprise the best approach for RM feasibility assessment due to some of the following reasons:

RP processes capabilities are usually compared among additive technologies and not against conventional manufacturing routes. RP Material databases are not used for evaluating functional capabilities of the different technologies. Key critical properties for end use application such as mechanical, thermal and functional properties have not been accounted as selection criteria. Databases developed for RP materials and machine parameters are not comprehensive enough to allow for RM assessment. More cases need to be developed and documented.

This research proposes an integrated RM selection system that includes an expert system, a fuzzy inference engine as well as two databases: materials and process capabilities, in order to support quantitative and qualitative data to be entered by the user. In addition the concept of "critical multipliers" is introduced which refers to those critical conditions that must be fulfilled for a certain task (e.g. critical structural part,

insulating material, flame retardant, etc.). The basic operations are basically performed by matrices and vectors, so that the non-fulfilment of any of those conditions may lead to the multiplication of the final vector by 0, automatically discarding the respective process. The final goal of this module is not to select the proper Rapid Prototyping process, but the identification of RM alternatives that can be adopted as feasible manufacturing options.

## 5.2 The RMADS selection module architecture

The Rapid Manufacturing advice system (RMADS) is intended to support designers during the earlier design stages to assess the possibility of using RM as a valid manufacturing route. It uses state of the art knowledge on RP/RM besides a series of previous case studies for verification purposes (Mahesh, 2005, Lan, 2005, Jiang and Hsu, 2003). Moreover a knowledge base obtained from local users, service bureaus and engineering centres (Munguía, 2007) is used in order to capture preferences and usual practices during design for RM. The architecture of this first RMADS Module is displayed on Figure 5.8. It shows the different elements working together with data extracted from two main databases to support the decision making task. The model is based on an object-oriented methodology (Masood and Al-Alawi, 2002) i.e. it is capable of working with independent modulus performing event-driven calculations according to user selection.

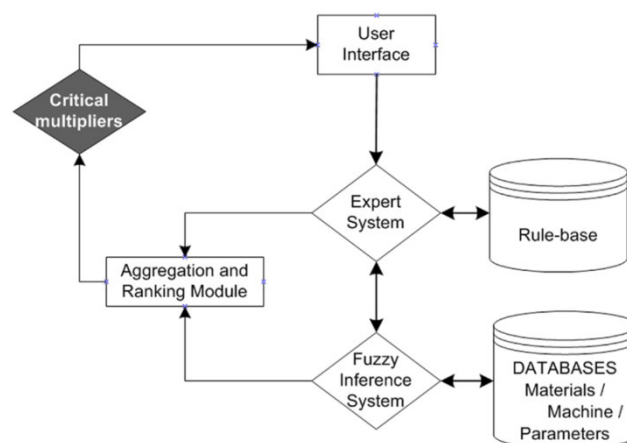


Figure 5. 8 Scheme of the RMADS Process Selection Module

### 5.2.1 The elements of the RMADS Process Selection Module

**User interface:** The user-interface accepts two types of input data: numerical and linguistic terms. Numerical values are quantitative data directly entered by the user while linguistic terms belong to those qualitative characteristics that must be chosen from a pre-defined list with a 3-level attribute (e.g. High, Average, and Low). Any of the 20 input options can be individually activated thus, as a result of such modularity each selected parameter will form a vector, with size equivalent to the number of RM processes stored in the database. The vector values are normalized in the range [0, 1].

**Expert system and its Rule-base:** The expert's knowledge is represented as a series of IF-THEN –ELSE statements. A total of 500 rules are executed when all the options of the system are activated, however the number of rules is due to increase with every new material and process added to the database. The importance of each rule is defined by the type of data handled as is explained in the following section.

**Fuzzy inference system:** This stage basically consists of representing all the goals and constraints as fuzzy sets (Zimmerman, 1991) obtained by mapping the membership values based on the selection of linguistic

variable by the user (Mahesh, 2005). Depending on the variable chosen (e.g. Surface Roughness, Tolerances, Mechanical properties, etc) the user will be presented a number of suitable options (e.g. high/average/low, etc.),

During the first tests of the RMADS interface it was suggested by users that multiple choices for a large number of parameters might lead to a long confusing selection procedure, therefore for the RMADS system a three-grades options approach will be used for each parameter.

**Database:** Two different databases store data regarding 1) RM Process parameters and individual machine information. 2) Materials database. Data has been gathered from available vendors info, related literature (ASERM, 2006, CASTLE-ISLAND, 2007, eFunda, 2007) as well as from other electronic data (Matweb, 2008, GRANTA, 2007). Data is stored in an Ms Access® database and called from the system by the Matlab® database toolbox (Mathworks, 2006).

**Aggregation and ranking module:** This module performs the final decision based on the parameters and options selected. Since qualitative information is normalized to 1 and qualitative information is treated as fuzzy numbers, the function of this module is to perform a fuzzy-decision. Although there exist a number of different approaches for ranking fuzzy sets (Carlsson, 1996, Raj and Kumar, 1999) each one with different advantages and drawbacks, for this paper the “transformation method” as applied by Lan et al. (2005) is adopted for this system.

5.2.2 A detailed description of Module 1

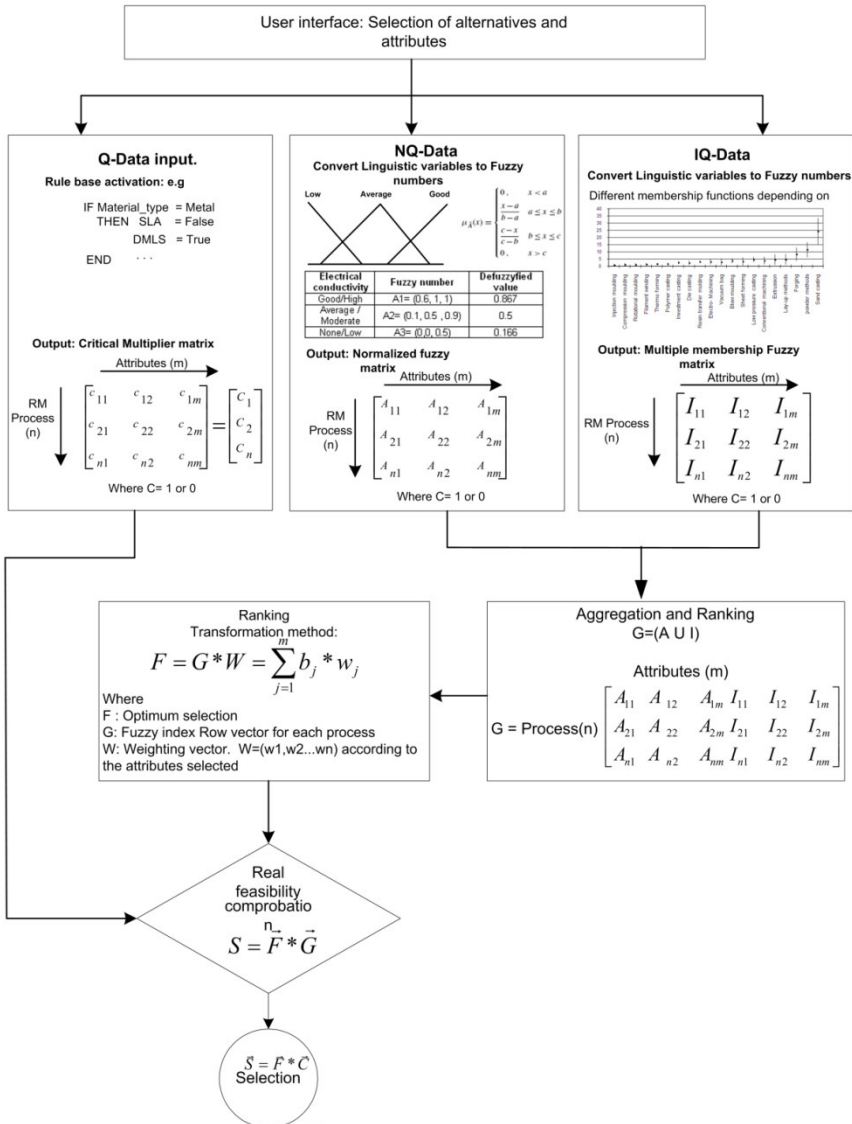


Figure 5. 9 The proposed Rapid Manufacturing Advice System algorithm

Methods based on fuzzy logic have been previously used in order to provide a uniform way of ranking different criteria during process/material selection (Brechet, 2001). Lan et.al.,(2005) go much further to state that it may be also considered a multi-alternative fuzzy decision-making problem. The RMADS system is intended to aid the designer on making appropriate decisions in presence of multiple attributes by following a straightforward procedure. Input information is accepted, normalized and converted to fuzzy numbers. Corresponding vectors are formed for each process. The size of the vector depends on the number of attributes selected as shown in Figure 5.9. Vectors are ranked according to the aggregation results.

5.2.3 Types of input parameters

Determining the correct input for the system is important for creating a more robust selection tool however this task is rarely straightforward. According to previous systems for RP selection (Bibb et al., 1999, Shercliff and Lovatt, 2001, Masood and Al-Alawi, 2002, Campbell and Bernie, 1996). Necessary input parameters are the classified by their type in:

- Design related. Design information and specifications (dimensions, volume, shape, surface finish, etc.)
- Production related. Parameters required for further cost estimation (required batch size, production rate)
- Processing and materials related. Depend on process specific parameters (scanning speed, laser spot diameter, chamber temperature, etc.) and materials specific properties (tensile strength, tensile modulus, elongation, impact, wear resistance, etc.)

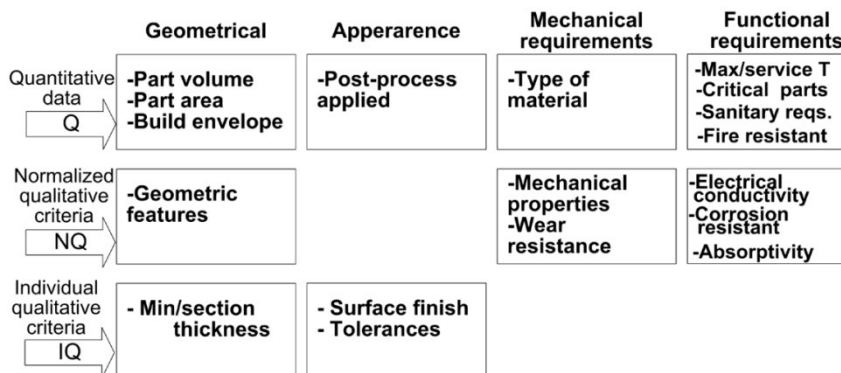
Previously developed computer based Rapid prototyping selection systems take into account a number of input factors attending the main requirements of these additive type technologies. Table 5.1 shows a number of parameters included as a system input by some previous RP selection tools.

**Table 5.1 Input parameters considered by different RP systems**

<i>IRIS RP selector</i> <sup>1</sup>	<i>RP advice system</i> <sup>2</sup>	<i>RP database</i> <sup>3</sup>	<i>Rule based RP system</i> <sup>4</sup>
RP machine price	Batch size	Material type	Machine price
XY& Z axis accuracy	Min wall thickness	Tolerances	Dimensional accuracy along X Y and Z
Build volume	Max aspect ratio	Internal features	Surface finish
Material	Accuracy	Max. XYZ dimension	Part bounding box
Surface finish	Intended material		Material type
Layer thickness	Final use		Layer thickness
Build speed			Process speed
Machine size			

<sup>1</sup> Masood and Al-Alawi, 2002 <sup>2</sup> Bibb et al., 1999 <sup>3</sup> Campbell and Bernie, 1996 <sup>4</sup> Masood and Soo, 2002

Through a search of conventional process and materials selectors commercially available (Dewhurst, 2007, GRANTA, 2007, TeamSet, 2005) along with the previous information it was possible to define a number of common parameters for conventional and RP/RM processes. These will be used as the RMAD system input as shown in Figure 5.10.



**Figure 5. 10 The 4 main categories for parameter input and its data type**

The main decision criteria are divided into 4 main subjects: Geometry, Appearance, Mechanical Requirements and Functional requirements each of them with different types of data used which receive different treatment. It can be inferred from the previous Table that while some parameters help refining the identification of suitable processes, others such as the Functional requirements play a more discriminating role for discarding any process which does not fulfil certain condition.

### 5.3 Inference engine definition: The system's logic

Once defined the input parameters to be considered by the RM advice system the next step is to define the inference structure to handle all user preferences. This is also called inference engine or combination engine.

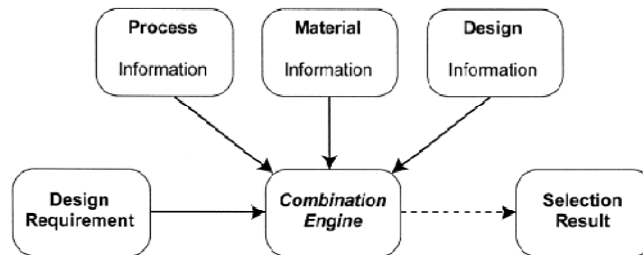


Figure 5.11 Elements of a material/process selection tool (Shercliff and Lovatt, 2001)

The selected input parameters may lead to an effective discriminating method named coupling (Shercliff and Lovatt, 2001), where the selection of certain processing preferences necessarily guides to the co-selection of the material and vice versa. Whether this is made by means of relational databases, graph information and screening, an important aspect of a selection tool is the way how the initial alternatives presented to the user will be combined as well as defining on what basis are to be ranked in order to provide a proper selection, making it a multi-criteria decision problem. Previous studies as the ones mentioned in the state of the art of RP systems selectors are based on a rule-based representation with conditional structures such as IF-THEN or CASE STRUCTURES, making it difficult to obtain a suitable ranking specially when vague data or non numeric values are involved, therefore the use of fuzzy sets has been included in recent selection models (Byun and Lee, 2005).

Bréchet et al. (2001) have used fuzzy logic methods in order to provide a uniform way of ranking different criteria during process/material selection while Lan et al. (2005) go much further to state that it may be also considered a multi-alternative fuzzy decision-making problem.

Due to the ability of fuzzy logic to deal with both types of data, (quantitative and qualitative) a fuzzy inference engine will be implemented for the present model. The challenge is to construct a useful model for handling precise (quantitative) and imprecise or vague data (qualitative, opinions, etc.) in order to translate this data into a fuzzy quantitative method (Mahesh, 2005) to arrive to a possible best solution, as few research works are based in this integration.

#### 5.3.1 On the use of fuzzy logic in the selection model

Fuzzy logic was first introduced by Zadeh (1965) as a method for mimicking the ability of human reasoning using a small number of rules and still producing a smooth output via a process of interpolation. Fuzzy set logic provides a strict mathematical framework in which vague conceptual phenomena can be precisely and rigorously studied. It can also be considered as a modelling language well suited for various situations, accordingly, fuzzy set theory provides a solution on limits to the usefulness of the mathematical language (Byun and Lee, 2005) as it forms rules that are based upon multi-valued logic and so introduced the concept of set membership.

With fuzzy logic, an element could partially belong to a set and this is represented by the set membership (Schmid, 2005). For instance, a person's height may be classified as: Tall  $> 1.80$  m, not tall  $\leq 1.80$  m. In a binary valued logic the membership of the attribute "Height" changes radically from one state to another with a difference of 1, 0.1, and 0.001 for both sides as shown in Figure 5.12. On the other hand by using

fuzzy logic, a height of value 1.79 m could still belong to both sets and, as the height value increases the membership for the attribute “Tall” would increase, while the membership value for “not tall” would be reduced.

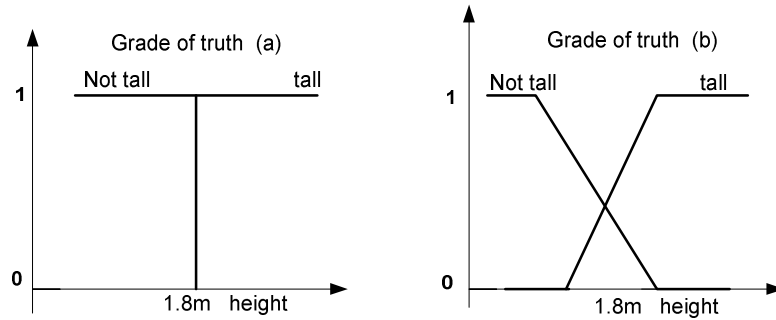


Figure 5.12 Differences of binary valued logic (a) and fuzzy logic (b)

Consider for Figure 5.13 the membership function  $\mu_A(x)$  that describes the membership of the elements  $x_i$  of the base set  $x$  also called “universe of discourse” in the fuzzy set A. Although a large number of functions may be chosen, less complicated membership functions are usually preferred such as triangular or trapezoidal. The fuzzy membership value for element  $x_0$  is described by membership  $\mu_A(x)$  and  $\mu_B(x)$  which determine the corresponding value in set A and set B between the range [0, 1].

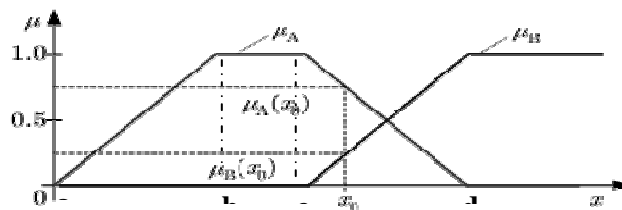


Figure 5.13 Trapezoidal fuzzy membership

Trapezoidal or triangular functions are defined by four and three parameters respectively. For triangular functions the only change is  $b=c$  in order to reduce it to three values (a,b,c).

$$\mu(x, a, b, c, d) = \begin{cases} 0, & x < a, x > d \\ \frac{x-a}{b-a} & a \leq x \leq b \\ 1 & b < x < c \\ \frac{d-x}{d-c} & c \leq x \leq d \end{cases} \quad (1)$$

While for some decision problems it is more convenient to use triangular memberships, especially for well defined data clusters with a single crisp value, for other decision making problems it might be more convenient to use trapezoidal functions as they have a longer crisp set, or core. The core is the set inside a given fuzzy membership function that contains all “x” elements whose membership grade is one (Figure 5.14).



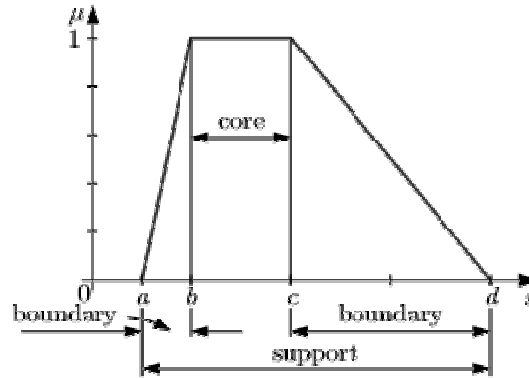


Figure 5.14 Characteristics of a trapezoidal membership function(Schmid, 2005)

Where

(2)

Under this premise some qualification schemes are frequently used in order to translate linguistic terms into fuzzy numbers. Chen and Hwuang(1992) proposed a numerical approximation method to systematically convert linguistic terms to their corresponding fuzzy numbers based on a 11-point scale, while Rao and Padmanabhan (2007) and Chen (1997) proposed a reduced scale of five grades with a trapezoidal membership as shown in Table 5.3.

Table 5. 2 Fuzzy numbers for the corresponding 5 scale linguistic terms

<i>Linguistics terms</i>	<i>Fuzzy numbers</i>
Very low (VL)	(0,0,0, 0.3)
Low (L)	(0, 0.3, 0.3, 0.5)
Medium (H)	(0.2, 0.5, 0.5, 0.8)
High (H)	(0.5, 0.7, 0.7, 1)
Very high (VH)	(0.7, 1, 1, 1)

Although the previous discussion might seem trivial, when designing a user interface with multiple options for process selection, a reduced range of options can make a more efficient and easier to use system. For the Rapid Manufacturing advice system proposed here, a three point-scale will be used with a trapezoidal membership function. The process is detailed in the following section.

#### 5.4 Assigning fuzzy grades to manufacturability options

Three different types of data are recognized for the proposed system as shown in Figure 5.10:

- Quantitative data (Q)
- Normalized qualitative criteria (NQ)
- Individual qualitative data (IQ)

##### 5.4.1 Quantitative data (Q)

It is also the most discriminating type since the non-completion of its requirements may result in the process being ruled out of the selection.

This data is processed by means of an expert rule base for each parameter. The rule base has been developed with the aid of process databases, previous papers results, as well as with observation and expert consultancy during field testing.

**Part build envelope (Variable name: Pbox\_X, Pbox\_Y, Pbox\_Z)**

The part's bounding box is requested to the user along with the measure of the part in the X, Y, Z axis as those parameters dictate a number of manufacturing aspects: the comparisons with the machines build volume on the 3 axes, the number of parts to be nested inside the chamber and its possible orientation. This may be a restricting factor since the work envelope of most RM processes continues to be relatively limited ranging from 250cm<sup>3</sup> to almost 1m<sup>3</sup>, however currently used materials give always the opportunity for welding, bonding or using a variety of joining options.

**Part Volume. (Variable name: Pvolume)**

The part's volume is requested in order to evaluate space requirements and cost approximations. The value can be obtained from any CAD/CAE software or from conventional STL file viewers, as long as the part has been modelled by a solid-based CAD system.

One rule base example is shown in Figure 5.15 where a comparison is performed between the values entered by the user and the database values for build envelope and X-Y-Z axes, in order to evaluate the feasibility of the processes stored in the system database. One of the advantages of the RM advice system here proposed is that besides comparing the part's and machine's build chamber size, it will perform a double calculation as follows: When the part's total volume and the values for the 3 axes (X, Y, Z) are entered the system will compare if the length, width and height can be merged inside the build chamber of every machine stored in the database. In the case one of the part's axes is bigger than the machine's, the system will perform a volume comparison so it will recommend a change of orientation during the build, a part slicing or in the worst case it will just rule out the RM equipment that can't handle the size and volume of the part.

```

FOR n = 1 UNTIL (Last RP machine in the database)
  IF      Pbox_X <= MachineX axis
    AND Pbox_Y <= Machine Y axis
    AND Pbox_Z <= Machine Z axis
  THEN   Machine(n) = TRUE
  ELSE IF Pvolume <= (Machine build volume)
    Machine(n) = True
  Print (" Consider slicing or sectioning the part")
  ELSE
    Machine(n) = FALSE

```

Figure 5.15 Sample rule base for comparing the part's and machines build volume

**Area (Variable name: P\_area)**

The part's area is included as a quantitative parameter. It won't be used as a screening factor but it'll be used in further modules for cost and time estimations as specified before. A number of approximation methods to define the part's area have been made (Wilson, 2006) however the most straightforward method is the use of a CAD system to obtain a precise value.

**Material Type (Mat\_type)**

Although not of a numeric nature as the previous parameters, the selection of the material type will guide automatically to the co-selection of the process following the process/material compatibility chart included in Annex 5.2 . The type of materials, as displayed by the system are:

- Metals
- Polymer
- Ceramic

- Composite
- Any (which includes photopolymers, wax and any other different material)

The corresponding rule base will confirm or rule out those RM technologies that cannot process the selected material type as shown in the Figure below.

```

IF Mat_type = Metal
THEN SLA = False
    DMLS = True
    FDM = False
    ... (all processes without metal compatibility ) = False
IF Mat_type = Polymer
    FDM = True
    SLM = False
    EBM = False
    ... etc.

```

Figure 5.16 Sample code for selection material type

### Post-process applied

This parameter deals with each Rapid manufacturing process' compatibility with different post-processing machines. The amount of post process time is directly dependent on the process capabilities. Those RM process that make use of support structures of hard to remove materials will be given longer times, which might be considered as an advantage between winning processes. Specially for cost-calculation post-processing is an issue to be considered. Data collected from published literature provides mainly qualitative information for different processes, defining the post-process requirements as: high, short, medium. The list considered in the RMADS system includes:

- Machining
- Polishing
- Painting
- Plating
- Sanding

### Maximum service Temperature (Variable name: Max\_temp)

In the case this option is activated by the user it will accept numeric values as an input. By means of a database search the system will search for every material available whose min and max values fit between the work temperatures entered by the user. Similar to the previous, the selection of the winning candidates will guide to a co-selection of the processes capable of processing them. That is another step in the global alternatives screening. The applied rule base is performed as follows:

```

For n=1 until (Last RP Material in the database)
  IF Max_temp <= Material_temp(n)
  Then Process_name(n) = true
  Else
    Process_name(n) = False

```

Figure 5.17 Sample code for retrieving material temperatures form the database

### Critical/ structural parts/ sanitary requirements/ Fire retardant / Electrical conductivity

Those four parameters will be enabled just when there're special needs for the design. The critical and structural option will be enabled by the criteria of the designer who decides whether the failure of the part or mechanism might result in risky or dangerous consequences to the system.

The sanitary consideration refers to whether the intended part or mechanism will be in close contact with human skin, internal organs or any kind of living matter. Also refers to contact or direct manipulation of food, nutrients and any substance that might be affected by exposure with a certain material that is not properly graded or certified. To date very few Rapid Manufacturing materials have been assigned such a property. For instance the Polyamide PA2200 processed by the EOSINT P 380 laser sintering machine for the fabrication of customized hearing aids, has been assigned a medical grade enough to be in contact with skin in the hearing channel (McBagonluri, 2008). Following this, the materials database stored within the RMADS system contains a registry of those materials already used with proven success for applications with some sort of sanitary requirements. The same is true for the Fire retardant and Electrical conductivity parameters which when activated, send a message to the system to retrieve from the materials database only those whose specification includes the property of “fire retardant” or a good level of electrical conductivity.

For the purpose of the proposed model, when any of those options or all of them are selected they’ll activate one of the most strict screening criteria since just a few materials have been recognized to fulfil these restrictive requirements. The selection of these parameters will determine whether a value 1 or 0 will be assigned. When 0 is assigned it causes the respective process ranking to be multiplied by 0, hence invalidating a certain process in accomplishing that function. The vector generated from this group of options corresponds to the vector “G” shown in Figure 5.9 at the beginning of the chapter.

### 5.4.2 Normalized qualitative criteria (NQ)

Information for these parameters is generally presented in variable terms depending on the data source, for instance the definitions of Surface Roughness found in different sources may be different. Usually available from textbooks and handbooks for a wide variety of processes this info is provided in units such as Ra ( $\mu\text{in}$  or  $\mu\text{m}$ ) mainly in America, and Rz mainly in Europe. This kind of notation considered as standard is defined on the basis of the ISO 4287 norm as the arithmetical mean of the deviations of the roughness profile from the central line along the measurement.

Although there are a lot of different techniques for evaluating the surface roughness, one of the most commonly employed methods for characterising roughness involves assessment of surface roughness average by means of stylus instruments (Costa, 2003). However this data is not always provided in the same form:

- Comparative ratings (A, B, C,D,E) with A indicating the highest value and E the lowest (ASM, 1997)
- Actual numeric values in Ra  $\mu\text{m}$  (Ashby, 2005)
- Actual numeric values Ra  $\mu\text{in}$  (Boothroyd, 1983)
- Qualitative grades like Good/Average/Bad (ASERM, 2006)

Therefore for attributes of this type it is preferred to assign Linguistic terms in order to generalize and appropriately represent this imprecise data for selection. These linguistic terms are then converted to fuzzy numbers following the procedures described on Figure 5.18.

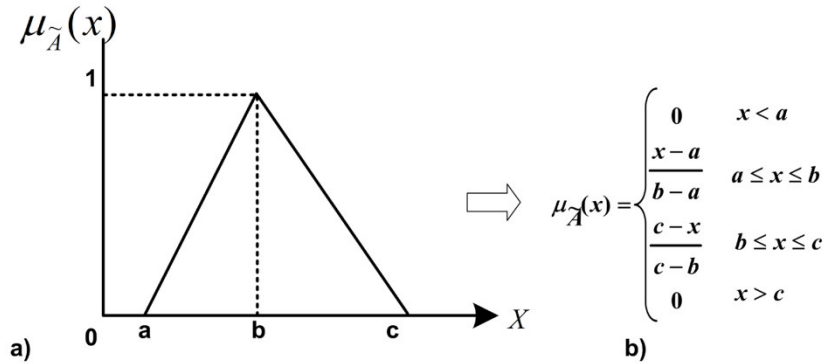


Figure 5.18 Linguistic term converted to fuzzy numbers by means of a triangular membership

Let a fuzzy number in  $R$  be a fuzzy subset in the universe of discourse  $X$ . A fuzzy set is represented by stating its membership function (Byun and Lee, 2005). A fuzzy set with a triangular membership function is represented as a triangular fuzzy number defined by variables  $(a, b, c)$ , and  $(\forall x, a, b, c \in R)$  then the membership function  $\mu_A(x)$  is defined as in Figure 5.18b. Following the function depicted above, linguistic variables used in the RMADS system are presented in Table 5.4.

Table 5.3 Fuzzy numbers assigned for different Linguistic Variables

<i>Corrosion resistance</i>	<i>Mechanical properties</i>	<i>Wear resistance</i>	<i>absorptivity</i>	<i>Fuzzy number</i>	<i>Defuzzified value</i>
<b>Good</b>	High	High	Low	A1= (0.6, 1, 1)	<b>0.867</b>
<b>Average</b>	Average	Average	Moderate	A2= (0.1, 0.5, 0.9)	<b>0.5</b>
None	<b>Low</b>	<b>Low</b>	<b>High</b>	<b>A3= (0,0, 0.5)</b>	<b>0.166</b>

The triangular membership functions for the three grades are described as: (1), (2) and (3).

$$\mu_{A1}(x) = \begin{cases} \frac{0.5 - x}{0.5} & 0 \leq x \leq 0.5 \\ 0 & x > 0.5 \end{cases} \tag{3}$$

$$\mu_{A2}(x) = \begin{cases} 0, & (x < 0.1) \\ \frac{x - 0.1}{0.4} & (0.1 \leq x \leq 0.5) \\ \frac{0.9 - x}{0.4} & (0.5 \leq x \leq 0.9) \\ 0, & (x > 0.9) \end{cases} \tag{4}$$

$$\mu_{A3}(x) = \begin{cases} 0, & (x < 0.6) \\ \frac{x - 0.6}{0.4}, & (0.6 \leq x \leq 1) \end{cases} \tag{5}$$

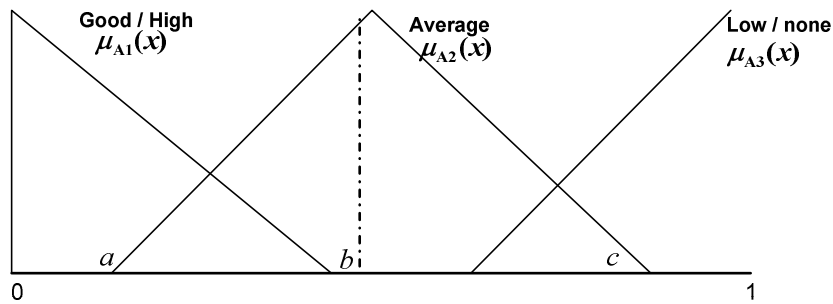


Figure 5.19 Triangular membership functions selected for the normalized qualitative criteria with the three grades for selection

The Defuzzified values shown in the last column of Table 5.4 were obtained using the centroid method. For triangular fuzzy numbers,  $\bar{v} = (a, b, c)$ , the defuzzification centroid value is given by (6).

$$\bar{v} = \frac{\int v\mu(v) dv}{\int \mu(v) dv} = \frac{1}{3} (a + b + c) \quad (6)$$

With this calculation, the decision maker by using the model will be able to input qualitative information by selecting Linguistic values based on his own criteria regarding different design parameters. These values will be translated to fuzzy numbers which after de-fuzzification will be ready for the next step of aggregation and ranking of the alternatives.

#### 5.4.3 Individualized qualitative criteria (NQ)

This type of input information is called “individual” since it’s not possible to apply uniform linguistic terms and the same membership function for each parameter as in the previous case. This criterion affects specifically to: Surface roughness, Tolerances, Min section Thickness for which the following steps are followed:

##### Data collection from databases and datasheets for conventional process capabilities

This step allows for setting the appropriate universe of discourse (X axis) for the different parameters used. The Figure below (Figure 5.20) shows the common limits for the attributes handled with this criterion. These limits correspond to conventional manufacturing; therefore the selection process takes into account conventional manufacturing and not only additive processes as the previously shown RP selectors.

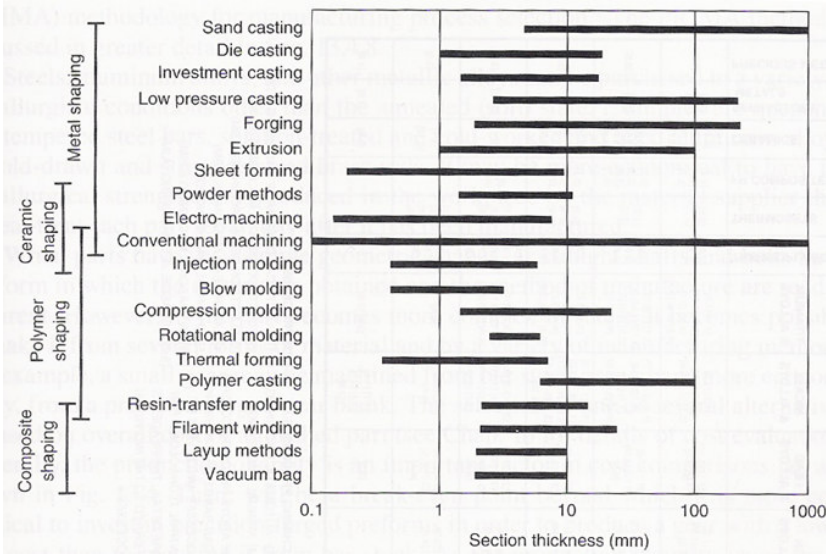
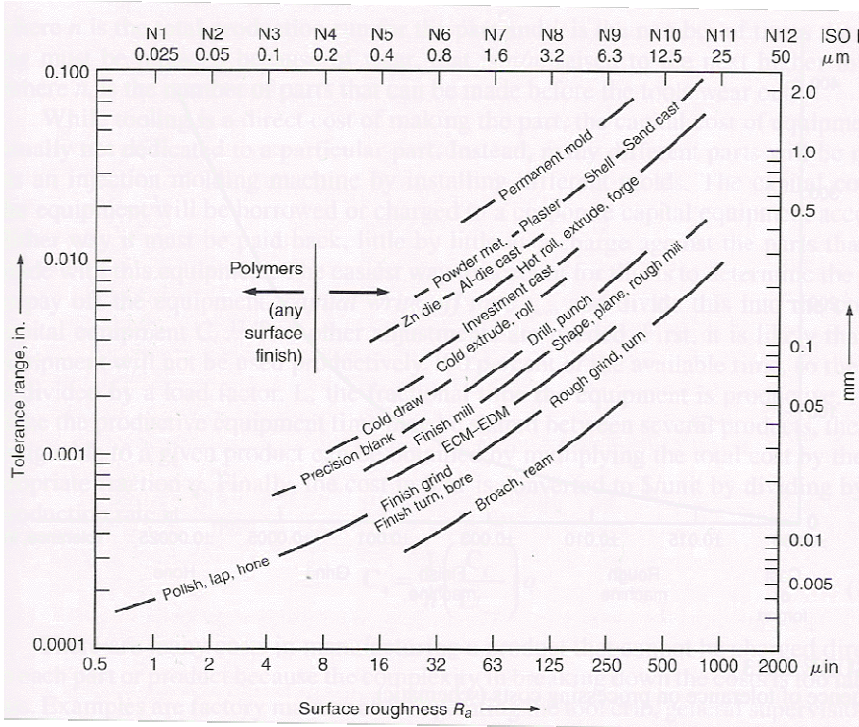


Figure 5.20 Approximate values of surface roughness and tolerance on dimensions (a) ,and section Thickness (b) typically obtained with different manufacturing processes. (Dieter, 2000)

**Classification of the process information**

From the same data sources besides consultancy with experts and previous papers on the same subject, the appropriate values for the different parameters were divided into three main values that will be presented as the options for every parameter of the RMADS system. The ranges selected for the three given parameters are shown in Table 5.4.

Table 5.4 Parameters with their corresponding 3-scale options

Min section thickness	Surface finish	Tolerances
Very Thin (0 - 0.5 mm)	Excellent (0- 3.2um)	Tight: $T \leq 0.1\text{mm}$
Thin- Avg (0.5- 2 mm)	Good-Avg (3.2- 12.5 um)	Average: $0.1 < T \leq 0.25 \text{ mm}$
Avg-Wide ( > 2 mm )	Avg-rough( $\geq 12.5 \text{ um}$ )	Loose: $T > 0.25 \text{ mm}$

**Mapping Rapid Manufacturing process information onto the conventional processes values.**

This is useful to understand until which point a certain RM option can perform equally or in some cases even outperform other conventional routes.

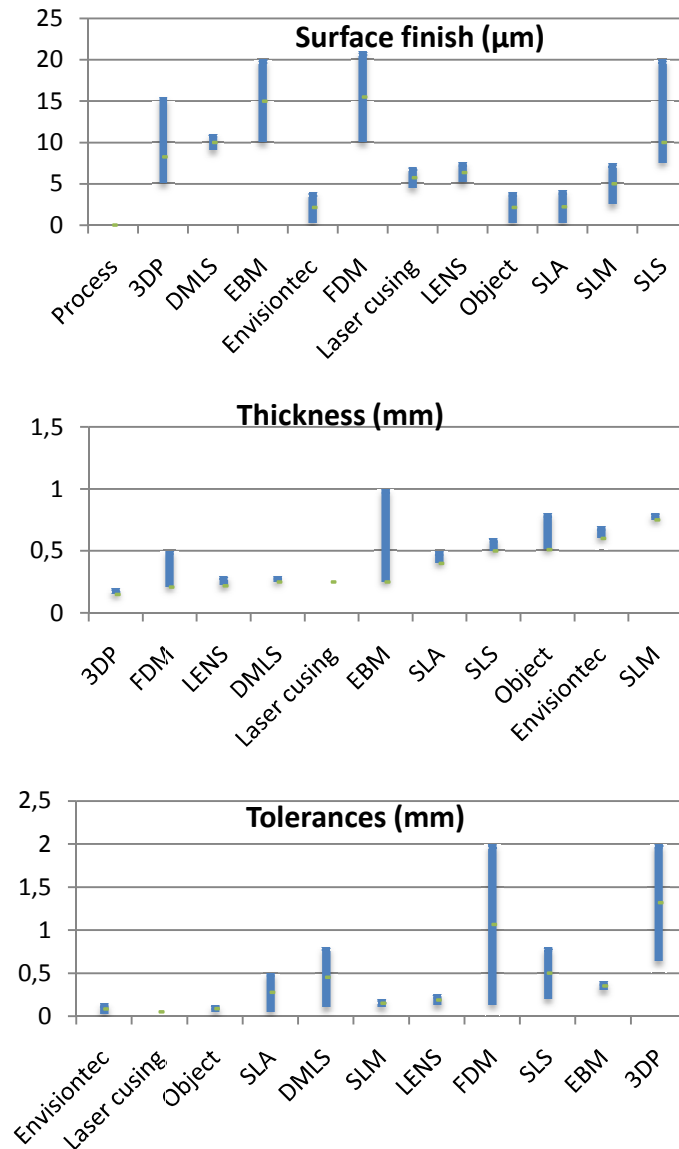


Figure 5.21 Rapid Manufacturing processes mapped on the conventional manufacturing scale for a) Surface finish, b) Thickness, c) Tolerances

**Establish membership functions and crisp data for original information.**

In order to assign fuzzy numbers to Individual qualitative data, a trapezoidal function for mapping the fuzzy membership will be used due to its effectiveness and suitability to our case. In the same way, membership grades are assigned to three linguistic variables as defined before.



As shown in Figure 5.20, the X axis or universe of discourse will be defined by the parameter values corresponding to conventional manufacturing processes and not to maximum values of RP processes as is the case of earlier RP selection systems. The form and membership type is not definitive and may be changed any time according to changes on the databases or according to the designer/engineer preferences.

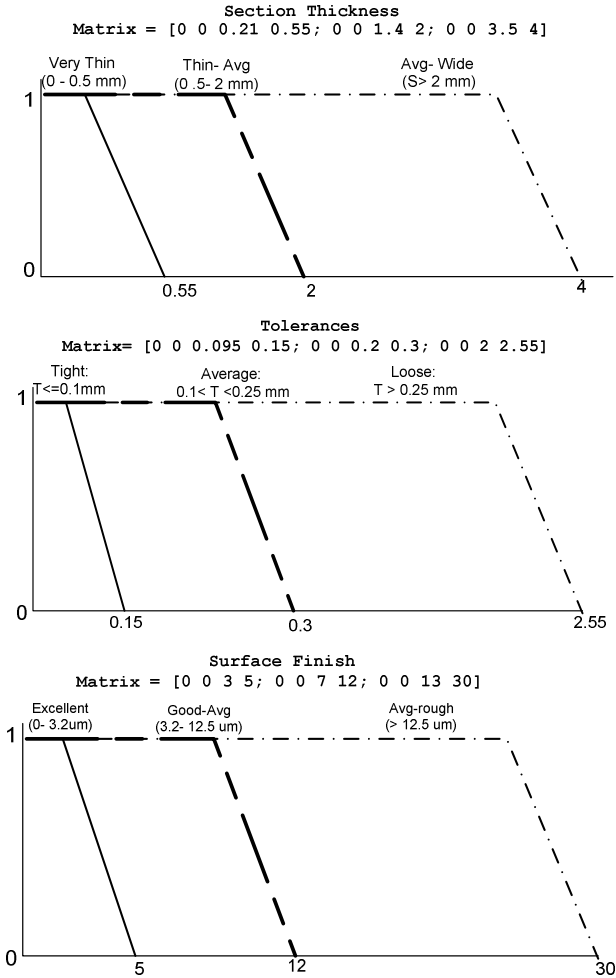


Figure 4.22 Fuzzy membership functions selected for the RMADS system

For instance for the Tolerance parameter, the linguistic variable set {Tight, Average, Loose} represents the crisp values used for the corresponding trapezoidal membership function. In order to get the maximum performance out of competing RP/RM processes a strategy called "positive discrimination" is introduced (Rao and Padmanabhan, 2007), where depending on the parameter selected the appropriate lower or uppermost value of the range will be converted to a fuzzy number instead of taking the mean value or triangular number. For instance, if the attribute "Tight" is selected for the tolerance parameter, the lowest value will be assigned (Figure 5.23, in the same way if the option "Loose" is selected, the uppermost value will be used).

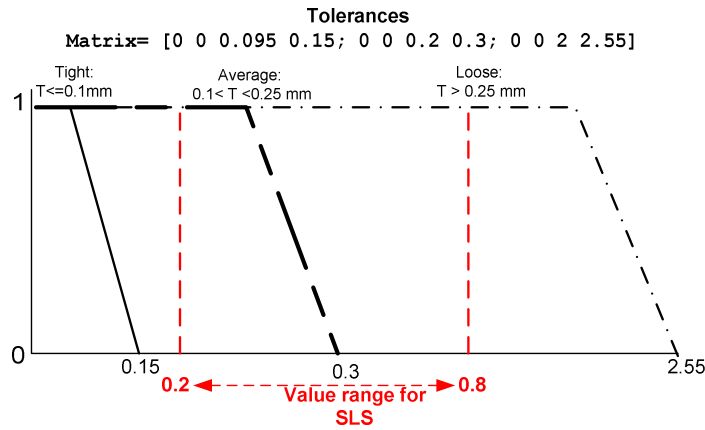


Figure 5.23 Trapezoidal membership function applied to the Tolerance attribute for SLS

### 5.5 Aggregation and ranking of selected objectives

Once the decision maker has selected the desired parameters by choosing the appropriate linguistic terms or by introducing data, the system builds one parameter vector for each competing process. This vector is the aggregate of fuzzy numbers obtained from NQ and IQ data as shown below.

$$G = \begin{matrix} \xrightarrow{\text{Number of attributes selected}} \\ \begin{bmatrix} A_{11} & A_{12} & A_{1m} & I_{11} & I_{12} & I_{1m} \\ A_{21} & A_{22} & A_{2m} & I_{21} & I_{22} & I_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & A_{nm} & I_{n1} & I_{n2} & I_{nm} \end{bmatrix} \\ \downarrow \text{Processes} \end{matrix} \quad (7)$$

Since not all the included parameters have the same importance for all design cases, the user is requested to grade the different selection boxes as:

- Not important
- Average importance
- Important
- Very Important

This corresponds to a 4 scale fuzzy numbers according to the importance given for a specific task: Geometry, Appearance, Functionality, and Mechanical Properties, where 4 is for the “Not important” and 1 is for the “very important” criteria. This leads to the creation of the weighting factor vector  $W$  shown in formula 8.

$$W = (w_1, w_2, w_3, w_4) \quad (8)$$

According to (Chen, 1992) the numeric scale entered by the user can be converted to fuzzy numbers following the triangular membership for a 4 point scale as shown in Figure 5.24.

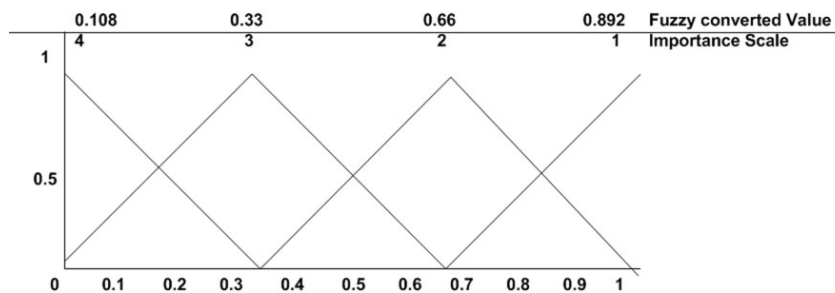


Figure 5.24 Fuzzy number conversion for a 4 point scale

Since the final selection will be comprised of 4 main categories, the aggregation matrix G is divided in 4 matrices which are normalized and then multiplied by W in order to perform the ranking procedure. For instance the Matrix corresponding to the Appearance factor that is comprised of two IQ parameters and one NQ parameter for each process as illustrated in (9).

$$M_{Appearance} = \begin{matrix} & \xrightarrow{\text{Processes}} & \\ \begin{matrix} A_{11} & A_{12} & A_{1n} \\ I_{21} & I_{22} & I_{2n} \\ I_{31} & I_{32} & I_{3n} \end{matrix} & \downarrow \text{Attributes} & \end{matrix} \quad (9)$$

The corresponding fuzzy numbers for the 3 attributes are then added for each process in order to get a final fuzzy grade. The same procedure is followed for the other 3 factors (10).

$$\sum M_{Appearance} = [S_{11} \ S_{12} \ S_{1n}] \quad (10)$$

$$\sum M_{Geometry} = [S_{21} \ S_{22} \ S_{2n}] \quad (11)$$

$$\sum M_{properties} = [S_{31} \ S_{32} \ S_{3n}] \quad (12)$$

$$\sum M_{Functionality} = [S_{41} \ S_{42} \ S_{4n}] \quad (13)$$

Consequently since the previous result might show uneven values for each process and among the 4 global factors (Geometry, Appearance, Functionality, Mech. Properties), the 4 vectors are aggregated in a single matrix and then normalized by equation (4) to obtain the final normalized matrix Mn (5).

$$M_n = \begin{bmatrix} N_{11} & N_{12} & N_{13} & N_{1n} \\ N_{21} & N_{22} & N_{23} & N_{2n} \\ N_{31} & N_{32} & N_{33} & N_{3n} \\ N_{41} & N_{42} & N_{43} & N_{4n} \end{bmatrix} \quad (14)$$

$$M_n(i, j) = S(i, j) / \sum_{i=1}^4 (M_{Ap_j}) \quad (15)$$

Fuzzy sets are ranked by a number of different strategies (Byun and Lee, 2005, Lee-Kwang, 1999)). Mahesh (2005) proposed the max-min method for a similar RP selection case; however it has the disadvantage of being predictable due to the final ranking being directly influenced by the worst-graded characteristic of each process. This bias can be addressed by alternative approaches such as the transformation method (Lan et al., 2005) based on normalization and posterior aggregation of the resultant vectors from the initial selection thus providing a more robust ranking method.

Let W= (w1, w2 w3, w4) be the weighting value vector resulting from the selection of the parameters importance. The final ranking is obtained from equation 16. This equation generates a single ranking value for each process where the vector W will be comprised of the user's criteria. The final verification is performed by applying the CM vector. As described before, it is comprised by critical criteria introduced by the user. Its use will be illustrated in the following example.

$$Ranking = M_n * W = \sum_{j=1}^n M_{nj} * W_j \quad (16)$$

## 5.6 Case Study

The sample part presented herein will also be included in the 'Case Studies Chapter' along with an in-depth analysis performed with the RMADS modules. In this section the functionality of the 'General Requirements Module' will be illustrated.

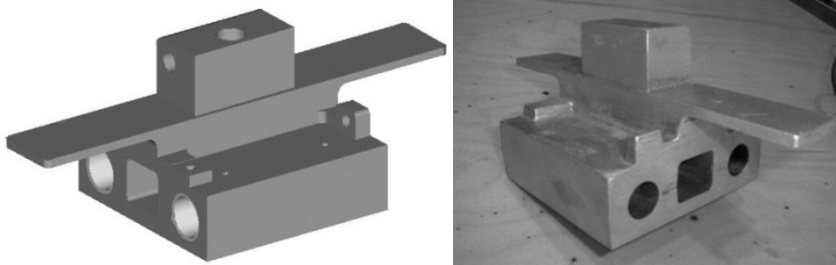


Figure 5.25 3D model of an internal mechanical part (a), and sand casted final part (b)

CDEI (Industrial Equipment Design Centre) was assigned the task to design a muscular relaxation device intended for the athlete's relaxation of the legs. Most of the internal parts were projected as sand casted elements due to lower cost for low volumes including the part shown in Figure 5.25 whose original design had to be modified in order to fulfil the restrictions imposed by sand casting (e.g. draft angles, constant wall thickness, avoid captured cavities, etc.). Furthermore the choice of sand casting included the difficult positioning of internal nucleus due to the design requirements.

The final part was made of Aluminium as shown in Figure 5.25b. However no critical functions had to be performed but the transmit ion of lineal movement. Therefore the part has two cylinders like trough-holes, for 2 vertical bars. Since it is an internal part there is not surface finishing or appearance considerations. Tolerances are neither an issue, one of the main reasons for using sand casting. However two special aspects suggested that RM should be explored as an option:

- 1- The part performs a non-critical function, i.e. it does not bear important mechanical forces.
- 2- The hollow cylinders need a low friction coefficient. A well known polyamide attribute.

The RMADS interface was used for entering the appropriate values according to the part requirements. It shows the iterative selection made by the designers in order to evaluate different options for the design and the result ranking. (Figure 5.26)

Table 5.5 Parameter selection for the previous screen

<b>Geometry</b>	<b>Importance: 'Important'</b>
Part Volume	382465
X measure	236.925
Y measure	110.966
Z measure	105.113
Min Section thickness	Avg-Wide (>2 $\mu\text{m}$ )
Geometric Features	Undercuts/Blind holes /Internal passages
<b>Functional Requirements</b>	<b>Importance: 'Average'</b>
Wear resistance	Average
Corrosion resistance	Low
Absorptive	Low
Max service Temp	100
<b>Appearance</b>	<b>Importance: 'Not Important'</b>
Surface finish	Avg-rough (>12.5 $\mu\text{m}$ )
Tolerances	Loose: T > 0.25mm
Post processes applied	Machining
<b>Mechanical requirements</b>	<b>Importance: 'Average'</b>
Material type	Any
Mechanical properties	Average

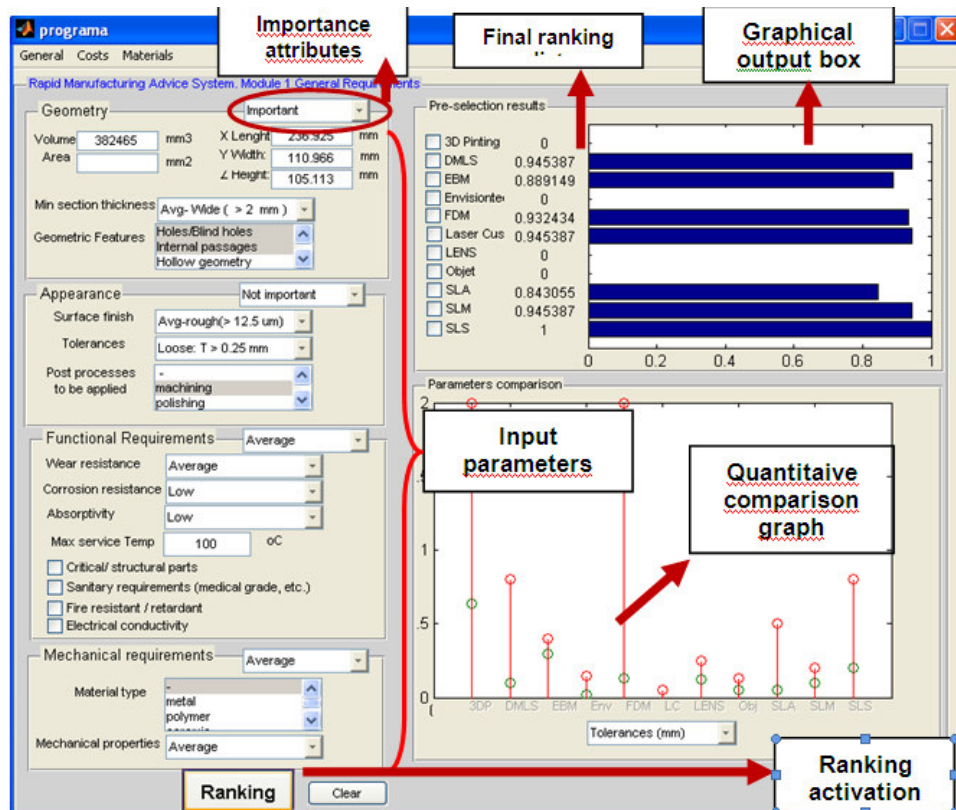


Figure 5.26 Graphical User interface for the RMADS system

Consider the info given in Table 5.6 as the data input according to the design specifications of the part. Note that Critical factors remained inactivated due to the nature of the function to be performed. As shown in Figure 5.26 the importance attributes for every category were assigned according to the following criteria:

Category	Importance Weigh
Mechanical requirements	Average
Functional Requirements	Average
Geometry	Important
Appearance	Not important

As shown in the previous figure, according to design requirements and the designer’s criteria, Selective Laser Sintering (SLS) and other metallic processes (DMLS, SLM, Laser Cusing) would be possible alternatives to be in depth explored. It is important to highlight that only three processes have been discarded during the selection process (3D printing, LENS, Objet) since there are not materials stored in the materials database with Temperature information. Although metallic processes would seem to be more appropriate to replace the original aluminium sand casted part, they may present difficulties due to the geometrical features needed and the post-processing operation to remove the necessary support structures (undercuts, internal passages and hidden holes); therefore the SLS process has a slight advantage in the final ranking in spite of the weaker mechanical properties it can provide.

The following illustration (Figure 5.27) shows a sensibility test in the final ranking when two different operating conditions are modified.

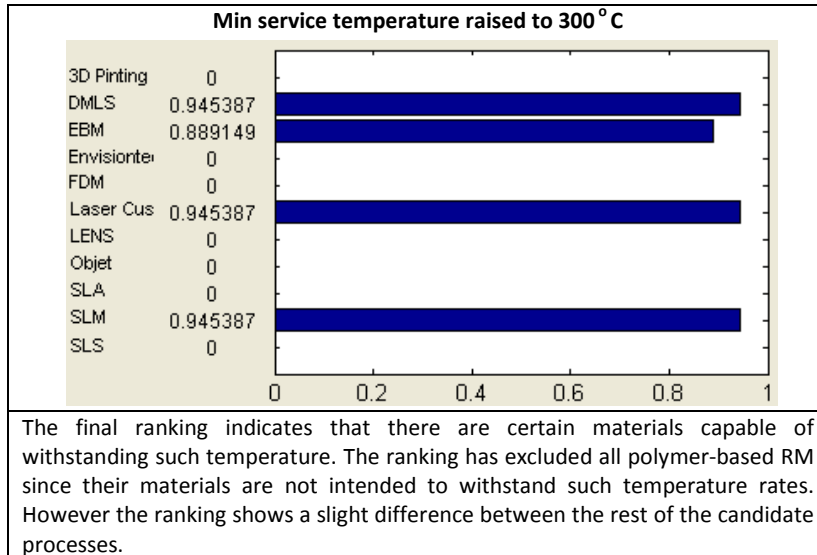


Figure 5.27 a) Final results given by RMADS

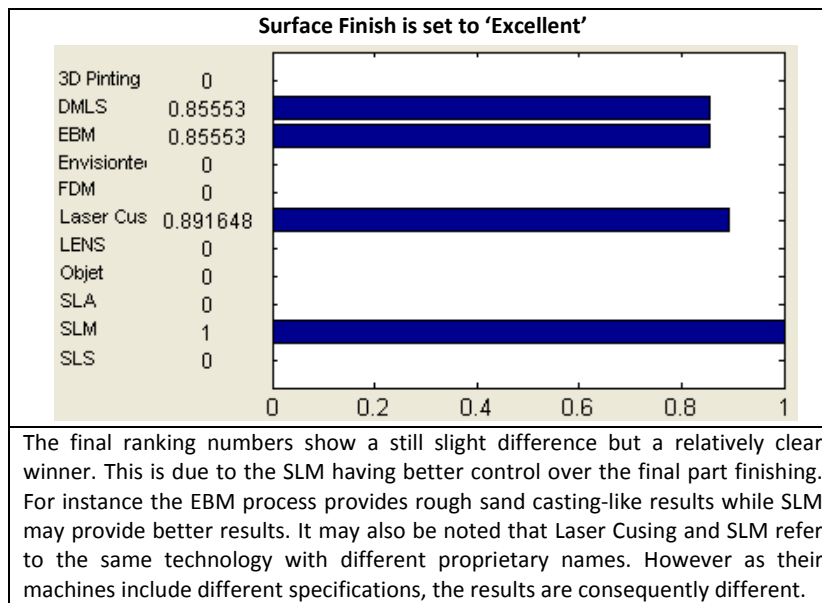


Figure 5.28 b) Final results given by RMADS

5.6.1 Numerical illustration of the example

A demonstration with the data provided in the previous case study is shown below. Let  $G(i, j)$  be the matrix that resulted from the selection made in Figure 5.26.

$$G(i, j) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0.42 & 0.42 & 0.61 & 0.61 & 0.42 & 0.42 & 0.61 & 0.61 & 0.42 & 1 \\ 0.85 & 1 & 0.58 & 1 & 0.52 & 1 & 1 & 1 & 1 & 1 & 0.58 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0.5 & 1 & 1 & 1 & 0.87 & 1 & 1 & 1 & 1 & 1 & 0.9 \\ 0.1 & 1 & 1 & 0.16 & 0.86 & 1 & 1 & 0.5 & 0.86 & 1 & 1 \\ 0.16 & 1 & 1 & 0.16 & 0.5 & 1 & 1 & 0.16 & 0.5 & 1 & 0.86 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0.16 & 1 & 1 & 0.16 & 1 & 1 & 1 & 0.16 & 0.25 & 1 & 1 \end{pmatrix} \quad (17)$$

Where  $i$  = Number of attributes activated by the user. And  $j$  = number of processes being compared. Then the matrix is divided into the four main categories as shown in the user interface where attributes pertaining to each category are arithmetically added.

$$\begin{aligned}
 \Sigma \text{Appearance} &= (2.0 \quad 1.4 \quad 1.4 \quad 1.6 \quad 1.6 \quad 1.4 \quad 1.4 \quad 1.6 \quad 1.6 \quad 1.4 \quad 2.0) \\
 \Sigma \text{Geometry} &= (2.3 \quad 3.0 \quad 2.5 \quad 3.0 \quad 2.4 \quad 3.0 \quad 3.0 \quad 3.0 \quad 3.0 \quad 3.0 \quad 2.4) \\
 \Sigma \text{Properties} &= (0.3 \quad 2 \quad 2 \quad 0.3 \quad 2.3 \quad 2 \quad 2 \quad 0.6 \quad 2.3 \quad 2 \quad 2.8) \\
 \Sigma \text{Functionality} &= (0.1 \quad 1 \quad 1 \quad 0.1 \quad 1 \quad 1 \quad 1 \quad 0.1 \quad 0.2 \quad 1 \quad 1)
 \end{aligned} \tag{18}$$

As the final step let  $W = (w_1, w_2, w_3, w_4)$  be the vector corresponding to the weighting factor entered by the user. For this example  $W = (0.333, 0.108, 0.666, 0.892)$ . By applying formula (15) and (16) the previous matrix is normalized to obtain a uniform vector (19).

Process	3DP	DMLS	EBM	Envis	FDM	L.Cus	LENS	Object	SLA	SLM	SLS
Ranking:	0.64	0.93	0.87	0.67	0.90	0.93	0.93	0.7	0.83	0.93	1

(19)

Although the previous vector shows normalized results for presenting an appropriate final ranking, it is necessary to refine and screen these results according to the remaining critical factors. That is, the so called ‘Critical multipliers’ presented in this section, appear as the last screening step so that only the most appropriate processes survive the final ranking. For this example the final resulting vector would be as shown in (20).

Table 5.7 Final ranking for the presented example

Process	3DP	DMLS	EBM	Envis	FDM	L.Cus	LENS	Object	SLA	SLM	SLS
Ranking:	0.00	0.93	0.88	0.00	0.90	0.93	0.00	0.00	0.83	0.93	1.00

(20)

The only critical multiplier activated for this example is the Max Service Temperature, which prevents a number of RM processes for being selected: in the case of Envisiontec, Objet and 3D printing due to the lack of suitable materials, while LENS is being ruled out due to the lack of materials information.

For this selection module a ranking scale from [0 -1] has been selected due to its similarity with previous selectors and familiarity for the user. A suitability of 1 is considered the optimum grade and reveals a high suitability of a given technology to perform a given task, similarly to other conventional manufacturing alternatives.

### 5.7 Conclusions

The proposed method contributes in filling the gap between conventional manufacturing knowledge and the actual knowledge on Rapid Manufacturing. Although the real value of the system will depend on the ability to feed the databases and monitor upcoming materials and new technology developments, it contains an appropriate logic for the selection or recommendation of a suitable RP/RM alternative.

While most of the RP equipments are being used as prototypes generators it is interesting to explore the possibility of approaching manufacture. Since every design case is different, what is normally an inappropriate process for a certain task may be a quite good candidate for another, as long as the critical constraints imposed by the designer are fulfilled.

The next step for developing a more robust RM Advice system is to integrate a cost analysis module. Although previous RP selectors include different sorts of cost factors or weights according to independent studies and surveys, for real manufacture a qualitative estimate is not always useful and may not provide valuable information for a decision maker.

Although the final ranking vector presented in this Module does not make a definitive selection it is intended to be combined with the rest of the modules to achieve a more informed and complete selection. On the other hand it must be born in mind that many parameters of this first module can be customized for different users. For instance, the fuzzy membership functions, their limits, and the importance vector weights can be manipulated in order to satisfy different criteria. Hence this might be one of the first selection systems capable of being customized to different users and their criteria in manufacturing.

A final ranking lower than 1 would show that the correspondent process is less likely to respond with the same efficiency that other manufacturing routes. This module by itself provides basic information on processes' comparison, therefore it must be complemented with the remaining RMADS modules.

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# 6. Cost Assessment for Rapid Manufacturing

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## *Abstract*

*Chapter 6 presents an overview on the cost assessment usually adopted for Rapid Manufacturing. It starts with the definition of common costing approaches in engineering, followed by a review of usual cost assessment for RM. It emphasises the use of different types of parametric estimators usually followed in academia and industry. Among these estimators it is possible to find curve-fitting based calculations, formulae-based and historic- information based. Finally the most usual models are implemented by a MatLab application so that their actual error rates can be directly compared.*

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### 6. Cost Assessment for Rapid Manufacturing

#### 6.1 Introduction

Cost estimation is concerned with the prediction of costs associated to a set of activities before they have actually been executed (Shehab and Abdalla 2001). Product costing is one of the most intensive and decisive activities during the design process. It doesn't only dictate the product's future success when released to market but also influences every decision made during the development cycle. Cost is usually the key point for decision making, with break-even points for different manufacturing technologies comprising the dominant information for decision makers.

The importance of cost estimations during product design is between some others:

- To provide information to establish the selling price and /or quotation
- To compare and determine the most economical method for manufacturing
- To establish cost identification and reduction activities
- To assess the profitability of a new design from early stages
- Select the most appropriate strategy: design to cost/design for cost

The appropriate costing strategy is important for the correct cost allocation for a given product or set of products however a bad selection may lead to distortions of cost information specially when allocating overhead costs (Tuncel, Akyol et al. 2005). Different design stages from concept design to manufacturing require different strategies in order to provide cost estimations to be used as parameters of the design efficiency. Also, the cost of modifying or correcting a design error rises considerably as product development proceeds through its phases therefore appropriate costing strategies must be established since the very first design stages (Hoult 2000). Before proceeding to describe the cost estimation method used by the system being proposed in this work, it is important to include a brief description of cost models used for traditional production methodologies. As the most common costing methods are depicted, their main differences with the needs of RM costing will arise, hence allowing to establish their differences as well as future needs for an effective RM cost model.

#### 6.2 Methods of developing cost estimates

Diverse literature for manufacturing cost estimation, show distinct classifications of cost evaluation methods. Since the focus of this research are mechanical parts or mechanisms generated by a certain number of processes, it is important to restrict the discussion in order to achieve sensible results. While some products even with moderate complexity, need from 3 to 5 different processes where costs must be considered, more complex products usually widen the number of processes to be analysed (domains of cost) hence it is of great importance to choose the right estimation method that suits the designer's needs. Some of the more recognized costing methods to be used in product design engineering (Dieter 2000; Hoult 2000; Cavalieri 2004) are:

1. Analytical models (Methods engineering)
2. Costs by analogy
3. Parametric models
4. Intuitive method

##### 6.2.1 Analytical models

They facilitate the identification of the ratio between overheads and direct labour costs due to the detail used to analyze separate elements of cost. The estimated cost of the product is calculated as the sum of its elementary components, tracking all the value resources used in each step of the production process (raw materials, components, labour, equipment, etc.). Due to the high level of detail used by these methods,

they can be used only when all the characteristics of the production process and of the product are well defined (Cavalieri 2004).

### 6.2.2 Costs by analogy

It is based on retrieving information from past designs and historical info in order to estimating future costs for a current design. It requires a comprehensive database of published costing data and constant updates especially regarding materials costs and other parameters that might have changed over time. This method is by far the most common in use since it's possible to account for only major features of the design to relate them to features of previous designs, ignoring details with little or minimum cost implications. Typical accuracy for these models goes from 15 to 25%, although it depends on past cases and an effective feature correlation strategy.

### 6.2.3 Parametric models

This is considered a statistical approach to cost estimation since it makes use of techniques such as regression analysis and curve fitting to establish a relationship between initial cost and selected process parameters. It makes use of a number of characteristics or parameters such as: mass, volume, weight, etc. From this simple description of the product, an estimate of its overall cost is developed. The key to achieve relative accuracy with this method is a careful limitation of the domain of cost. The accuracy expected from parametric models is about 30% being a generally accepted method especially for the conceptual phases of the design.

Three basic types of parametric models are described by Duverlie and Castelain (1999):

- The method of scales: Suitable to predict cost for simple products of variable sizes, based on the most representative product features. However one of the major disadvantages of this method is the assumption of a linear relationship between the value of the considered"
- Statistical models: It is based on the statistical relationships for parameters of different domains of the product, where a mathematical formula is developed to describe the relationship and generalise further cases. It is based on determining variables and constants.
- Cost estimation formulae (CEF): Is a simple mathematical relationship between a limited number of product parameters (between 2 and 5) and the cost. Its main disadvantage is that parameters must be selected by experts.

### 6.2.4 Intuitive method

It is based on the experience of the estimator. The result is always dependent on the estimator's knowledge. This method is highly subjective and requires extensive experience. There are also a number of methods being currently applied to cost estimation which are related to the use of Artificial Intelligence (AI) techniques. Roy (2003) and Rush (2000) include in their classification some AI methods namely: Neural networks, Case based reasoning and Expert systems that will be discussed later in this chapter.

It is important to highlight that the use of one method alone is not always sufficient. For example variable costs which are different for every part and depend on certain conditions such as process set-up and pre-processing costs, are well fitted to the analogy based methods, while a parametric method is preferred for the assessment of material costs. Figure 6.1 shows different cost assessment methods and their recommended use through different design stages.

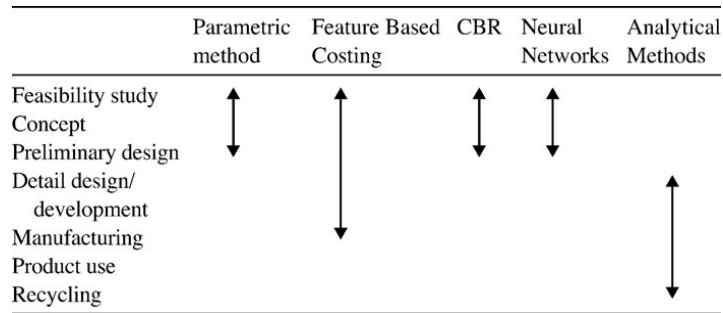


Figure 6. 1 Applicability of the cost assessment methods at different stages of the product lifecycle Source (Wrobel and Laudanski 2008)

It is not often possible to get large cost reductions once production has begun because of the high cost of change in latter design stages of the product life cycle. Therefore, the earlier costly designs can be identified, the sooner the product planning can be corrected and optimized.

As costing models become more detailed the need for specific information grows making it difficult to accomplish an accurate-comprehensive analysis when the required proprietary info is not at the analyst’s disposal. Therefore many efforts have been made in order to achieve reasonable cost estimations with as few parameters as possible. Table 6.1 presents a comparison chart with advantages and disadvantages for selecting certain method for a given case.

Table 6. 1 Comparison of the main cost estimation methods

	Advantages	Disadvantages
<b>Parametric methods</b>	<ul style="list-style-type: none"> <li>-Work better with variants of earlier designs</li> <li>- make clear the influence of parameters on the economic value of the product.</li> </ul>	<ul style="list-style-type: none"> <li>-They have an empirical nature relying on historical info.</li> <li>-Works like a “black box”. Difficult to understand important cost drivers and their impact to cost.</li> <li>-If the context changes, its necessary to remake an estimation</li> <li>-For the model to work the user must enter all parameters or estimate the missing ones.</li> </ul>
<b>Analytical</b>	Very accurate definition of technological processes and cost allocation	Slow method its comprehensiveness makes it unpopular for software estimators
<b>Analogy based</b>	<ul style="list-style-type: none"> <li>-Their capacity of reasoning on past experiences avoids the formalization of knowledge in the form of rules as Rule-based systems do.</li> <li>-It is possible to call on the intuition, the judgement and the habits of the expert</li> <li>-Fast and easy to develop compared to rule-based systems</li> </ul>	<ul style="list-style-type: none"> <li>-he source and target cases must strictly belong to the same universe</li> <li>-is less easy than in the case of the parametric method because it is necessary to provide the cases base, the indexation of cases, the similarity measure and the adaptation functions.</li> </ul>
<b>Intuitive</b>	<ul style="list-style-type: none"> <li>-relays on experienced designer’s and engineer’s knowledge making it subjective</li> <li>-The estimated cost may be a rough over or under estimation</li> </ul>	<ul style="list-style-type: none"> <li>- Its fast and straightforward</li> <li>-Since its based mostly in previous experience they usually lead to realistic estimations</li> </ul>

According to the previous chart the selection of the appropriate costing model can be achieved by identifying the current design phase and the information available from the product. It is also possible to



apply more than one method to get comparison of distinct domains, for instance assembly costs can be determined using the analytical approach while the analogy based method can be applied to different processes according to geometric and other features.

### 6.3 Costing models for Rapid manufacturing

Decisions taken during the design stages usually determine 70 to 80 % of the final cost of a product. Would this assumption change with the advent of Rapid Manufacturing? As design is becoming the bottleneck between an initial product concept and its actual fabrication, it's fair to believe that design not only will drive nearly 90 % of the cost but its expected to be the most labour intensive activity of the whole product development process.

Since Rapid manufacturing is the natural technology for low-volume high-added-value manufacture, contrary to the high-volume, low-added-value production paradigm (Kruf 2006) it must take advantage of different product strategies such as Mass Customization, Spare Parts, Parts on Demand between some other approaches (Freitag 2003).

Cost estimation for RM is a complex yet "tricky issue" since the final scope or utility of the product will define the methods to be used. Many companies do not disclose their experiences and financial data to Project proprietary info, the result is that there's a substantial info gap regarding the true cost of Rapid Manufacturing systems, their implementation and operation (Grimm 2004).

In well established manufacturing processes, analytical models are well known and guide unequivocally to reliable estimates. That's the case of machining, injection moulding or casting whose main cost drivers are well known and can be just "fed" to a datasheet once the intended part has been defined. On the other hand, parametric costing methods have been successfully developed for a wider variety of applications as they try to correlate relevant observed variables to a final "objective function". What all the previous conventional manufacturing cost-estimation methods have in common is: their estimation is intended for final production, making use of the full process capability.

It may not be necessarily true for RM processes whose "flexible nature" makes them ideal for single part production as for low volumes or in special cases, dedicated production. Whatever the case is, it is not possible to apply the same costing model for the all cases, making it necessary to first of all, define the production strategy. The three most widely encountered production strategies encountered are the following.

- Single part production: Though not common due to economical unfeasibility, there's a case where a single part with unique parameters, process style and size must be built, thus focusing the correspondent cost allocation to only 1 part.
- Mixed components. This can be the most common type of production for RM and also the most widespread among RM users & service providers. Since one single part may not be economically produced, the build volume is packed with different parts with the same functional requirements and consequently similar build parameters. Cost allocation is unclear and may rely on proprietary formulas for cost allocation, thus guiding to dissimilar estimations depending on the provider.
- Dedicated production: This is a special case which may be the ideal for RM. When the additive process has been in depth evaluated and certified based on repeatability and constant quality. Hence the RM process chosen can be applied to serial production thus adopting a different cost model than the previous cases.

If there is a difference to be highlighted between Rapid Manufacturing and other means of fabrication regarding costs estimation is that final part quoting must be instantly calculated. Due to its integration with CAD models and internet platforms and servers, companies offering RM and RP services must be capable of providing real time estimates based on precise costing models. There's not "one formula", but many being used by different providers and manufacturers to quote their RM-service, based on distinct cost drivers (direct, indirect and overhead costs) and their expected profit margins.

Even within a factory, there are many questionable costs, not directly driven by the type, number or volume of products. In addition, there are costs that are driven by substantial material vendors and customers. Several methods exist, and each company uses a method of its own.

It is not unusual in the RM industry to obtain completely different quotes for the same part, with the same process from distinct service providers. As each service bureau develops its own costing formula the levels of cost and profit margins lead to different estimates. Also, since the quoting method must be capable of detecting minor changes in the part to be reflected (or not) in the final cost, the quoting models used in the RM industry must be capable of identifying the most sensible parameters with the lowest number of variables as possible to achieve fast estimates and generate a robust cost estimation model.

### 6.4 Previous methods for RM cost estimation

Little work has been published on how to perform cost estimations or how to define the costing strategy for Rapid Manufacturing. One of the first works devoted to costing determination for RM was presented by (Hopkinson 2001; Hopkinson and Dickens 2003) which comprises the first analytical method to assess cost estimation for RM since most of the information about the part, build times, volume, etc. must be known beforehand. A detailed description of the method is presented in the following sections.

Ruffo, Tuck et al. (2006) designated time as the key parameter to be estimated in order to make a more appropriate cost allocation among different parts build by the same process. Ruffo proposed a Selective laser sintering time estimator which is based on a number of previous design cases for achieving rough estimates for new parts. It made use of curve fitting techniques in order to obtain a parametric model that could be used to predict build times. The resulting formula was split into three main time factors: recoating time, scanning time, pre and post processing time. Later on Ruffo, Tuck et al. (2006) came up with an improvement on the previous model including cost calculation where multiple different parts are packed in the same build. The research is based on Hopkinson and Dickens' model which was modified so as to consider low volume manufacturing.

Wilson (2006) developed a parametric time and cost estimation for a number of Rapid Prototyping processes (SLS, SLA, 3DP, FDM) based on a set of machine parameters provided by each manufacturer and a series of production parameters estimated empirically. The model was implemented as Matlab application in order to provide calculations regarding part volume, gap between parts, orientation angle and batch volume. The final estimated build time depends on a single variable ( $\alpha$ ) which needs to be readjusted for every different process & machine selected, thus comprising a source of uncertainty.

Phillipson and Henderson (1997) also developed a parametric cost estimation model for Rapid prototyping based on speed categories which assigns a different formula to a given number of RM processes according to the build speed parameters. The model is less comprehensive than Wilson's estimator and hasn't been compared to other similar systems. Luo, Tzou et al. (2003) also developed a parametric time/cost estimator however it's based on more generic parameters for every additive process like layer thickness, number of

layers, Z height, etc. The system is intended to operate within a web-based platform but no information or case studies are provided for this method.

Since RM methods can build different parts that require different build times, cost allocation for indirect costs is usually based on time. Therefore it's fundamental to have appropriate time estimations in order to calculate costs (Ruffo, Tuck et al. 2006). Chen and Sullivan (1996) studied the Stereolithography process obtaining build time estimation function based on parameters such as laser power, beam diameter, materials properties and cure depth while Choi and Samavedam (2002) investigated on the optimum part orientation methods for different RP processes and also developed a time estimation method for Laser Sintering based on laser speed, scan distance and layer thickness. However they arrived to a comprehensive method where imprecise data of a single parameter might compromise the correct estimation.

### 6.5 General cost drivers for RM

Cost drivers for Rapid Manufacturing can be diverse depending on the process studied. There are some evident ones such as the RM machine itself and its energy consumption, space requirements and operating cost. Other drivers comprise any ancillary equipment required for post-processing, but also the cost of hidden extras. These stem from two sources where the first source of hidden cost stems largely from

- The need to possibly modify existing computer-aided design systems
- Additional secondary technologies required to transform models into tooling and components
- Further equipment required to reduce and eliminate health and safety risks, and so on.

The second source of hidden costs stems from organisational and human resource issues. These account to more than just the obvious training costs associated with learning how to operate the new equipment (Kidd 1997). Wohlers (2006) pointed out the so called "*hidden costs of RM*" by showing the main costs that must be included in any RM costing model and others which are not usually taken into account. However this analysis focuses on investment on the equipment and its usual cost of ownership. Nonetheless this approach illustrates how machine costs are usually accompanied by remarkable secondary investments such as: third party software, post-processing equipment (ovens, wash tanks, hand tools, etc.), services (electricity consumption), maintenance agreements (as a rule 10% of purchase price of the RM machine), parts replacement, and materials.

### 6.6 Definition of the main cost drivers for Rapid Manufacturing

#### 6.6.1 Materials cost

From the above cost considerations, materials are one of the most important cost drivers. The prices per Kilogram of RM material are far higher than those from conventional manufacturing. Depending on the process used, materials may range from 54€ to 250€/kg. At this price, the cost of filling up a RM machine vat, for instance a SLA equipment would range from 4000 to 30.000€ depending on the available build volume.

Not only cost accounts for used material but also for the proportional waste produced. Also for Stereolithography due to the cumulative exposure to UV rays an entire vat of resin might become unusable for subsequent builds (Grimm 2004). The same is true for Laser sintering where prolonged exposure to heating inside the machine, leads to changes on the powder properties, degrading its capability to produce quality builds. Also during a normal build of typical individual parts it is expected that a considerable amount of material is not reclaimed thus creating a stockpile of unusable material. Although the scrap rate

for different processes and materials may differ, it is a fair assumption to plan for a 10% material loss per build (Hopkinson 2006; Wohlers 2006). At the end between 20 to 25% of the final part cost is usually allocated to materials alone.

**Table 6. 2 Approximate material cost for different processes (Hopkinson 2001)**

	Process/material	Cost per kg (\$)
Rapid prototyping/ manufacturing	Stereolithography/epoxy-based resin	175
	Selective laser sintering/nylon powder	75
	Fused deposition modelling/ABS filament	250
Conventional manufacturing	Injection moulding/ABS	1.80
	Machining/1112 screw-machine steel	0.66

### 6.6.2 Labour Costs

Labour costs allocation for RM may be cumbersome; although additive technologies are not characterized for being labour intensive but rather autonomous, there are a number of parallel activities that must be carried out for whom the costs account:

- Data management
- File preparation (design, file integrity checking, conversion, etc.)
- Machine and material preparation (set-up, cleaning, parameter tuning)
- Machine operation and construction verification
- Part extracting and finishing (post-processing should they apply)

In a recent study carried out among local engineering centres and RM service providers (Munguia, de Ciurana et al. 2008) the usual operating time for the equipment was signalled within a range of 10 to 16 hours uptime per day, this means a period of 70 to 112 hours of weekly operation. Participants were also asked to grade the activities according to the time they regularly consume during the RM process (Table 6.3). The results placed manual operation as a bottleneck for RM. The average time of manual labour goes from 2 to 3 hours per pre and post-processing cycles, part removal and preparation for the next build. This is concordant with Ruffo, Tuck et al. (2006) who consider an approximate Heating and Cooling time of 60 minutes per build for Laser Sintering once the operator has acquired sufficient expertise on the task.

**Table 6. 3 RM activities graded by the time usually consumed. (Munguía 2007)**

Position	Activities
1	Detailed finishing, painting, coating
2	Post process, curing, infiltration, etc.
3	RM process fabrication
4	Part orientation, support generation and STL conversion
5	Part extraction, support, removal and cleaning
6	CAD design and file export

Manual labour costs provided by the same cited study show values that go from 20 to 35 € per hour which are charged to the final part cost where roughly 30% goes as strictly direct labour cost. Though it is not the major cost when producing small runs, labour costs become more important when volumes increase. Since

many activities in Rapid Manufacturing are still labour-intensive this might be an area to be addressed by further research.

**6.6.3 Machine costs**

According to Hopkinson, Hague et al. (2005), machine costs for Rapid Manufacture are largely dictated by machine depreciation. This is confirmed by Munguia (2008) as shown in Figure 6.2, where from a survey of a number of engineering centres the main factors affecting final cost were machine depreciation, followed by maintenance and materials cost.

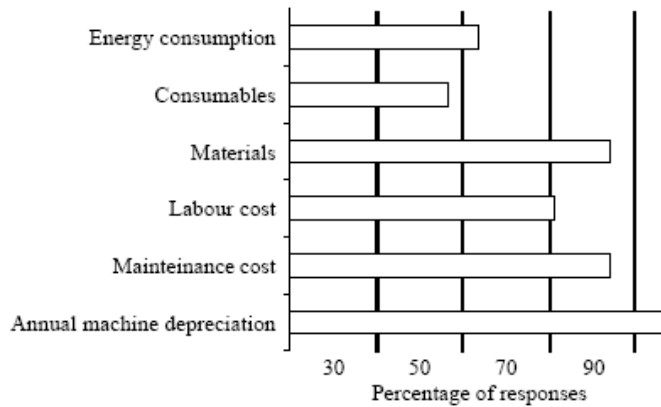


Figure 6. 2 Main factors influencing RM cost as determined from regional bureaus (Munguia 2008)

Depreciation is a changing variable which depends on the region where the equipment is operating. So while in the United States depreciation is calculated for periods of 7-10 years, some other regions such as Spain consider a depreciation period shorter than 6 years as shown in Figure 6.3.

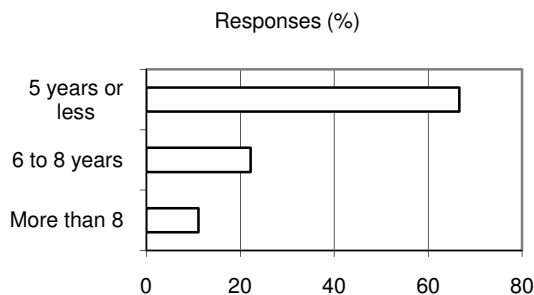


Figure 6. 3 Depreciation time considered by users: 5 years or less:67%, 6 to 8 years: 22%, More than 8 years: 11% (Munguia, de Ciurana et al. 2008)

Results in Figure 6.3 show a tendency for a quick return of investment while the equipment’s lifespan is increased by its appropriate maintenance. Although questions on the age of individual RP equipment were not included in the survey, it is common to find equipment from 8 to 10 years old especially for technologies that require major investments such as SLA and SLS. For the purpose of general estimations by consulted literature a period of 8-10 years is usually considered.

**6.6.4 Overhead costs**

Since labour time is reduced in RM, overhead cost allocation might slightly change for additive manufacturing processes. Manufacturing overhead, also referred to as “burden”, are those variable or fixed costs that must be assigned to each unit produced, which includes factors such as: the electricity used to operate the factory equipment, depreciation on the factory equipment and building, factory supplies and

factory personnel (other than direct labour). How these costs are assigned to products has an impact on the measurement of an individual product's profitability (Accountingcoach.com 2008).

From a RM approach, since there is a direct relationship between production time with overall part size and the number of parts to be produced, the key variable for RM is build time (Tuck 2006). Therefore it is reasonable to allocate overhead cost to the number of build hours that it takes to build a given number of parts.

The next section describes some of the latest cost and time estimation models developments. A general explanation of the model is made besides a description of the methods and equations used. The methods presented in this section will be reproduced as Matlab software modules with the intention of measuring their suitability as RM cost estimators and to compare their precision.

## 6.7 Currently used RM cost estimation models

### 6.7.1 Hopkinson and Dicken's cost analysis method. (Loughborough University, U.K.)

The RM costing method developed by Hopkinson and Dickens (2003) was meant to provide a direct comparison with injection moulding (IM) as it was assumed that the RM machine is making copies of the same part just like in mass production. This assumption leads to a constant- linear cost for RM while for IM there is a characteristic curve that depicts the initial investment of tooling and the consequent amortization of the tooling cost as the production volumes increase.

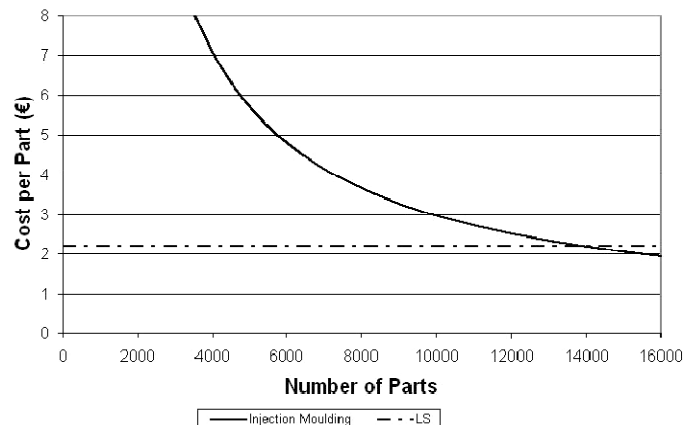


Figure 6. 4 Example of break-even analysis comparing LS with injection moulding. (Hopkinson and Dickens 2003)

It can be said that the assumptions used by this model may not match the real requirements for RM since some factors such as machine power consumption, space rental and overhead costs were assumed to account for a full annual production. It was also assumed that the RM machine would achieve 90 percent uptime in order to match the workload achieved by injection moulding. Main costs as considered by this model are broken down into 3 groups:

- Machine costs. In order to calculate total machine cost per part produced
- Labour costs. Required to formulate the labour costs per part.
- Material costs. The different nature of each process makes it necessary to use a special material cost calculation for each process.

Calculation of machine costs		
	Variable	Obtained by
Number per platform	N	Maximum possible
Platform build time	T	Hours
production rate per hour	R	N/T
Hours per year in operation	HY	365 x 24 x 90% = 7884
Production volume. Total/year	V	R x 7884
Machine costs		
Machine and ancillary equipment	E	Machine purchase cost
Equipment depreciation per year	D	E/8
Machine maintenance per year	M	Most comprehensive pack
Total machine cost per year	MC	D + M
Machine cost per part	MCP	MC / V
Calculation of labour costs		
	Variable	Obtained by
Machine operator cost per hour	Op	Minimum wage 5.3 euros
Set-up time to control machine	Set	Timed
post-processing time per build	Post	Timed
Labour cost per build	L	Op x (Set + Post)
Labour cost per part	LCP	L/N
Calculation of material costs for each process		
	Variable	Obtained by
Number per platform	N	Maximum possible in one build
Material cost for SL	SLMass	weighning finished parts
Material per part including support (kg)	SLcost	Quote = 275.2 euros
Material cost per kg	SLMCP	SLMAss x SL cost
Material cost per SL part		
Material cost for FDM		
Material per part (kg)	FDMPM	Weighning finished parts
Support material per part (kg)	FDMSM	Weighning finished supports
Build material cost per kg	FDMPM	Quote = 400. euros
Support material cost per kg	FDMSC	Quote = 216 euros
Material cost per FDM part		
Material costs for LS		
Material cost per kg	LSC	Quote = 54 euros
Mass of each part	LSM	Weighning finished parts
Volume of each part	VP	Found with Magics software
total build volume	TBV	34 x 34 x 60 cm3
Mass of unsintered material per build	LSMS	N x LSM
Mass of unsintered material per build	LSMU	(TBV - N x VP) x 0.475*
Cost of material used in one build	LSMC	(LSMU + LSMS) x LSC
Material cost per LS part	LSMCP	LSMC / N

Figure 6. 5 Costing parameters considered by Hopkinson and Dickens (2003)

Along the model it is possible to differentiate three main types of data that take part in the analysis namely: Empirical data, Assumed values, and formulae-calculated data.

Empirical data encloses the following parameters:

- Number of parts per platform: Obtained from the empirical parts distribution on the build bed
- Platform build time: Calculated with the machine's proprietary software
- Set-up time: Timed from a ser of routines
- Post processing time: Timed from a ser of routines
- Material consumed: By weighting finished parts and their support
- Parts Volume: Found with Materialise Magic's software

Between some of the assumptions made for this model, the following are found.

- Hours per year in operation: A 90% uptime is assumed; however from normal operation of RP and RM equipment, the percentage may well be lower. Ruffo, Tuck et al. (2006) estimated a 57% of habitual utilization.
- Machine operator cost per hour: 5.3€/hr was considered as a suitable amount. However it is assumed that highly skilled staff would not be needed. In practice, usual labour cost per hour range from 11 to 33€/hr (Munguía 2007) Which might be more realistic for getting cost estimations.

The last type of data corresponds to the results provided by the formulae and calculations depicted in Figure 6.5. While Hopkinson and Dickens provide a cost allocation method for Rapid Manufacturing, it may well be more suitable for mass production since the up-time percentage used (90%); labour costs and overhead allocation may not correspond to reality as most centres and service bureaus quote their parts based on 50- 60% uptime. Experience shows it is difficult to exceed 60% uptime for any RM equipment with their current usage (Ruffo and Hague 2007). While this method illustrates the RM cost graph as a constant line (Figure 6.6a, a more realistic cost graph for RM should reflect the influence on cost of an individual part and a subsequent addition of new parts to the build chamber just like in Figure 6.6b.

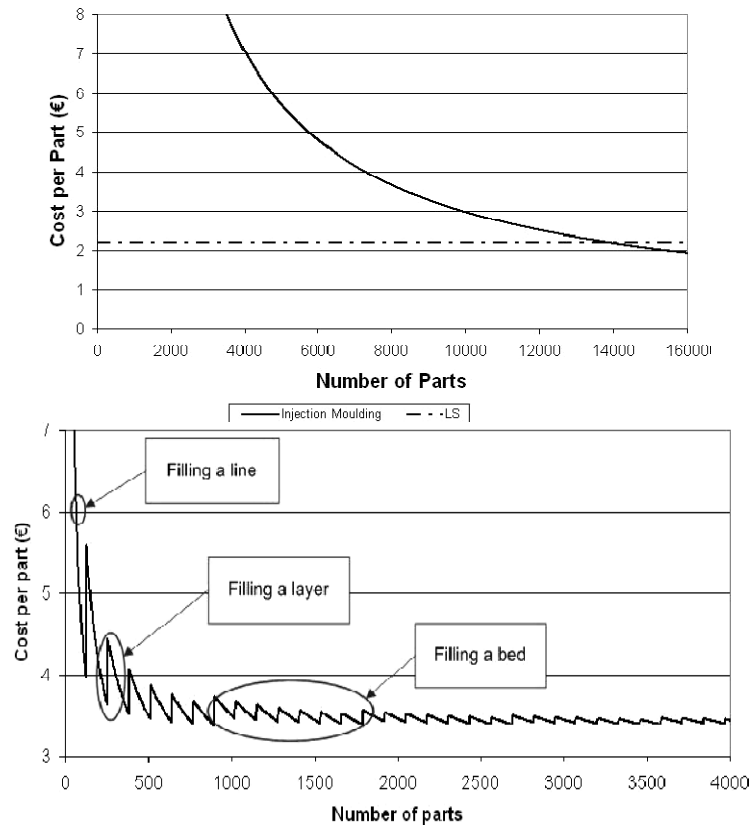


Figure 6. 6 a) RM costing graph provided by the Hopkinson & Dickens method where cost is a constant for different production volumes (linear) (Hopkinson and Dickens 2003) b) RM graph provided by Ruffo with differences in cost according to the build space used (Gig-saw type) (Ruffo, Tuck et al. 2006)

There're some drawbacks associated to this method as it requires having a build-time and pack-ratio estimates beforehand. Therefore, if it is to be used as an analytical method it may be fed by time estimations and parameters obtained from the RM machine's proprietary software. The Hopkinson & Dickens model has been codified as a MatLab Module in order to run a number of test for the validity and precision of the cost estimation (Annex 3).



### 6.7.2 Ruffo & Hague's Parametric/Analytic cost estimation method (Loughborough University, U.K)

The model presented by Ruffo, Tuck et al. (2006) is situated between the parametric model and the engineering /analytical approach since the main method for identifying relationships between process parameters is by performing statistical approximations. Originally the method is devoted to the Selective Laser Sintering process (SLS). By adopting a low volume approach instead of mass production this method aims at making approximated cost estimates based on two main modules:

- Time estimation method: based on curve fitting and regression
- Cost estimation: based on a detailed cost allocation system

The conceptual model is depicted in Figure 6.7 where the different elements of cost are broken down into: direct and indirect. Direct costs correspond to materials while indirect costs are related to labour, machine and overhead costs.

The cost of a build is calculated as the sum of indirect cost associated with build-time while direct costs are associated with the material consumed during manufacture as shown by equations 1-3.

$$\text{Cost}_B = \text{Cost}(t_B) + \text{Cost}(m_B) \quad (1)$$

Where:

$$\text{Cost}(m_B) = \frac{\text{direct Cost}}{\text{mass unit}} m_B \quad (2)$$

$$\text{Cost}(t_B) = \frac{\sum \text{indirect cost}}{\text{working time}} t_B \quad (3)$$

The working time refers to how long the machine works for the build. The advantage of this method is that it allows the calculation of material used including the non-sintered and wasted material during part cleaning or recycling. A waste factor is introduced which varies depending on each manufacturer's preferences. Therefore the final material consumption must be more realistic than other methods. However this might be a restriction for being applied to other RM processes.

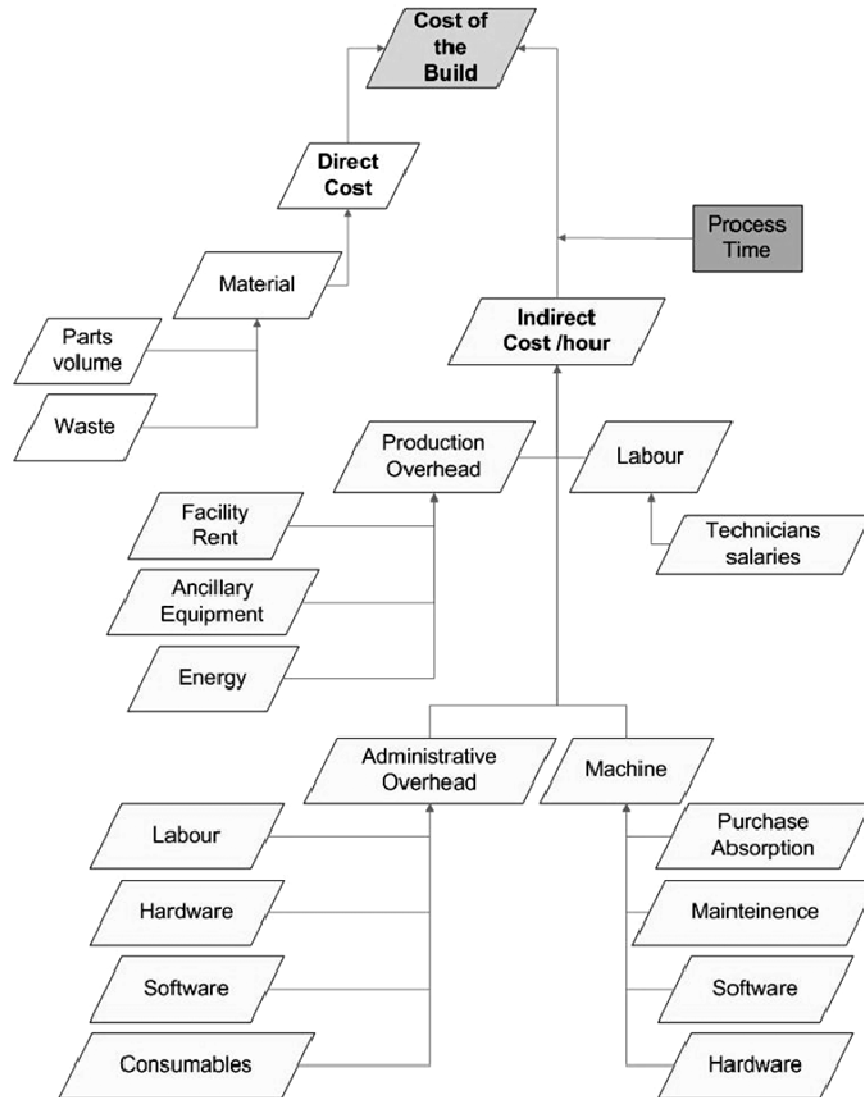


Figure 6. 7 Scheme of the costing model (Ruffo, Tuck et al. 2006)

The material used by the SLS process is defined by this model as equation 4:

$$m_B = \rho * (V_B + W_B) \quad (4)$$

where  $W_B$  is the volume of the material wasted,  $\rho$  is the material density and  $V_B$  correspond to the volume of the entire build. The second parameter considered for the model is the “packing ratio” expressed as a relation of the total volume of the parts included in one build chamber and the machine’s total bounding box:

$$PR = \frac{V_B}{V_{beds}} = \frac{V_p * n_p}{V_{beds}} \quad (5)$$

The packing ratio is one of the main cost indicators since it’s used as a measure of the space used for each build, which is a major driver for the final cost. The closer the PR is to 1 the lower the final cost per part will be. The third major cost driver is “build time” which is depicted by equation 6. It follows a similar approach to Wilson (2006) as it breaks down manufacturing time into three factors:

$$t_B = t_{xy} + t_z + t_{HC} \quad (6)$$

Where  $t_{xy}$  is time for area scanning,  $t_z$  is the layer deposition time and  $t_{HC}$  indicates the heating and cooling time.

A build-time estimator for the Selective Laser Sintering was previously developed by the same author (Ruffo, Tuck et al. 2006). The model relies on the empirical identification of the main cost drivers namely: part height, part volume and machine bounding-box volume. The author performed a number of tests with STL model data in order to define the different factors comprising an integrated build time estimation equation (7)

$$t_B = \vartheta * (0.042 * x^{-0.1809} * x * y) * z + (180 - 120 * \frac{V_{ext}}{V_{bed}}) * z + 400 + 3600 \quad (7)$$

Where:

- $t_B$  is the build time estimate
- $\vartheta$  is the ratio between the volume of the object (or build) and the volume of its bounding box where  $\vartheta \in [0, 1]$
- $X, y, z$  correspond to the length, width and height of the part
- $V_{ext}$  is the parts bounding box volume
- $V_{bed}$  is the volume of the complete machines vat

This equation however is the result of a series of tests on a Vanguard SLS machine and cannot be extrapolated to any other equipment, hence the same procedure for obtaining the approximation formula must be repeated for every RM process and machine.

### 6.7.3 Wilson’s parametric cost and time estimation model (Georgia Institute of Technology. EE.UU.)

The model developed by Wilson (2006) was included as part of a master thesis entitled: “Selection for Rapid Manufacturing under epistemic uncertainty” at Georgia Institute of Technology. It defines a string of well defined procedures to perform parametric cost estimations for number of Rapid Manufacturing technologies namely: SLS, SLA, and FDM. The model is universal in the sense that it strictly depends on the parameters that characterize each technology and the overall design features.

The parametric model proposed by Wilson is show in Figure 6.8. It shows the generic RM procedure while the build time estimation method is based on the parameters appearing in the 4<sup>th</sup> step.

Build time is defined as the total time required to build single or multiple parts. For RM, it is assumed that a full vat is used for manufacture. Therefore, the time to build the full vat is averaged among the number of parts per vat, giving an average build time per part. Before proceeding to calculate time and cost the system needs two parameters to be defined: Volume and the part’s bounding box, which determine the packing ratio ( $\rho$ ). This factor is important in order to determine the distribution of the sintering area and the velocity change of the laser.

Based on Pham and Gault (1998) the model makes use of a modified factor to account for the average scan area distribution  $f(\rho)$ :

$$f(\rho) = \rho * e^{\alpha(1-\rho)} \quad (8)$$

where

$$f(\rho) \leq 1, 0 \leq \rho \leq 1$$

The parameter  $\alpha$  which is to be empirically determined from experimental trials its one of the most important elements of the models and at the same time one of the main sources of uncertainty, since it must be adjusted for every different process, machine and operating conditions where the model is applied. The general model comprises 3 main modules: time estimation for single part, cost estimation for multiple parts and cost estimation for multiple parts.

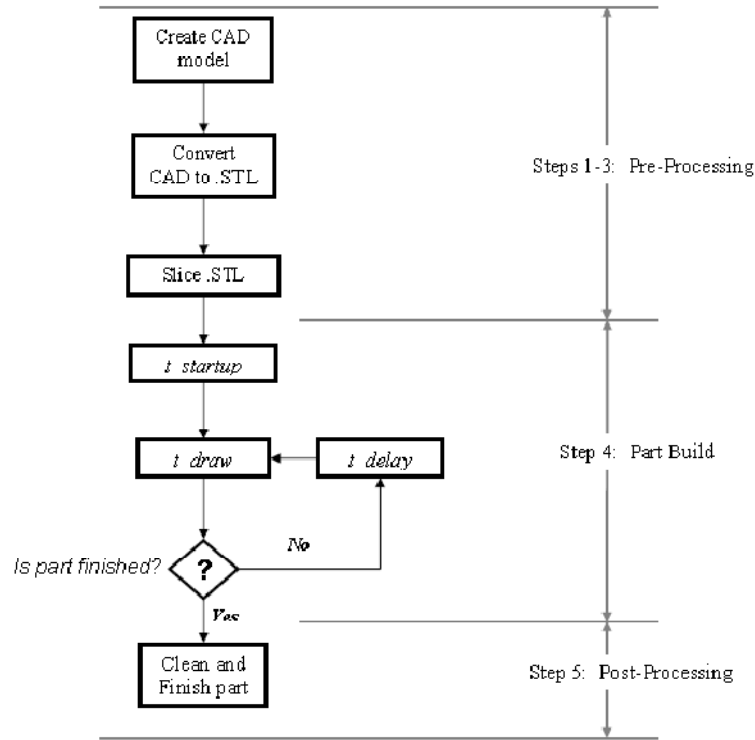


Figure 6. 8 Generic RP build-time process

#### 6.7.4 Parametric Build Time estimation

The model introduced by Wilson includes three main parameters influencing the total build time (equation 9). Annex 5 contains information regarding the parameters included in the following equations.

$$t_{\text{build}} = t_{\text{scan}} + t_{\text{delay}} + t_{\text{startup}} \quad (9)$$

Where  $t_{\text{build}}$  is the total estimated build time.  $t_{\text{draw}}$  describes the material deposition, solidifying, and sintering processes for a number of parts as expressed by equation 10.

$$t_{\text{scan}} = \frac{N_{\text{build}} * N_{\text{scan}} * A_{\text{avg}} \left[ \frac{Z_{\text{height}}}{t_{\text{layer}}} \right]}{D_{\text{scan}} * V_{\text{avg}} * \text{Hatch}} + \frac{N_{\text{build}} * N_{\text{scan\_supp}} * A_{\text{avg}} * \text{supp\_factor} \left[ \frac{Z_{\text{supp}}}{t_{\text{layer}}} \right]}{D_{\text{scan}} * V_{\text{avg}} * \text{Hatch}} \quad (10)$$

Where:

$D_{\text{scan}}$  = Scan (draw) diameter (length)

Hatch= Percentage overlap of scans (%)

$V_{\text{jump}}$  = jump velocity (mm/s)

$V_{\text{scan}}$  = scan (draw) velocity (mm/s)

$t_{\text{layer}}$  = layer thickness (mm)

$N_{\text{scan}}$  = 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)

$N_{build}$  = maximum number of parts in a single build

On the other hand  $t_{delay}$  is the time corresponding to the total time between scans as determined by equation (11)

$$t_{delay} = \left[ \frac{Z_{total}}{t_{layer}} \right] \left( t_{draw_{delay}} + t_{stg_{down}} + t_{stg_{delay}} + t_{stg_{up}} + t_{sweep} + t_{swp_{delay}} \right) \quad (11)$$

where:

$t_{draw_{delay}}$  = 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

The variable  $t_{startup}$  corresponds to warm up times which were approximated based on observation and available information.

### 6.7.5 Parametric Cost estimation

A parametric cost estimation method was also developed which consists of extracting the time estimation results from the previous model in order to get a total cost for the construction of a full vat. Then the cost per part is averaged among the number of parts inside the build space. Figure 6.9 shows the main elements of cost as projected by Wilson which comprise similar concepts when compared to the Hopkinson's method.

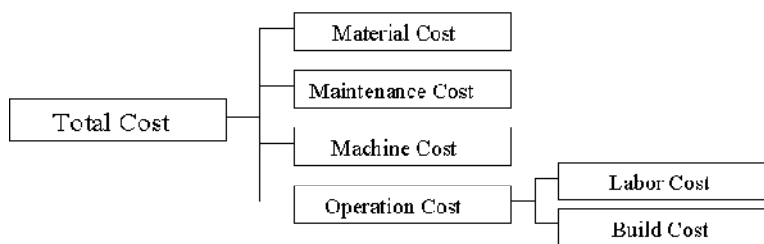


Figure 6. 9 Parametric Cost Model

The equations for cost and the corresponding parameter definition are shown in Table 6.4.

This parametric model can be as precise as the parameters used as input. In order to verify the performance of this method against the other RM cost estimation methods, the model has been codified using Matlab (Annex 3) and the comparison results are presented at the end of this section.

Table 6. 4 Formulae applied for the parametric cost estimation method

<p><b>Material Cost:</b></p> $C_{material} = (vol_{part} * dens (1 + supp_{factor})) MatC$	<ul style="list-style-type: none"> <li>• <math>C_{material}</math> has the units of (\$/part).</li> <li>• MatC = cost of material per unit weight.</li> <li>• vol_part = Part volume</li> <li>• dens = material density</li> <li>• supp_factor = support factor (approximate the volume of material used to build the supports)</li> </ul>
<p><b>Maintenance Cost</b></p> $C_{maintenance} = \frac{MaintC * N_{mach}}{365 * N_{ppd}}$	<ul style="list-style-type: none"> <li>• MaintC =per year contract term with the manufacturer.</li> <li>• <math>N_{mach}</math> = the number of machines used</li> <li>• <math>N_{ppd}</math> = number of parts per day,</li> </ul>
<p><b>Machine Cost</b></p> $C_{machine} = \frac{MachC * N_{mach}}{365 * ul * N_{ppd}}$	<ul style="list-style-type: none"> <li>• MachC= total machine cost</li> <li>• UI = useful life of the machine</li> </ul>
<p><b>Operation Cost</b></p> $C_{operation} = C_{build} + C_{labour}$ $C_{labour} = (t_{preproc} + t_{postproc})tech_{rate}$ $C_{build} = t_{build} * Mach_{rate}$	<ul style="list-style-type: none"> <li>• Mach_rate =cost of operating the machine per hour (\$/hr)</li> <li>• tech_rate =technician rate per hour (\$/hr)</li> <li>• <math>t_{preproc}, t_{postproc}</math> = times gathered from observation of pre and post processing activities</li> </ul>

### 6.8 Commercial cost estimation methods: Online quoting

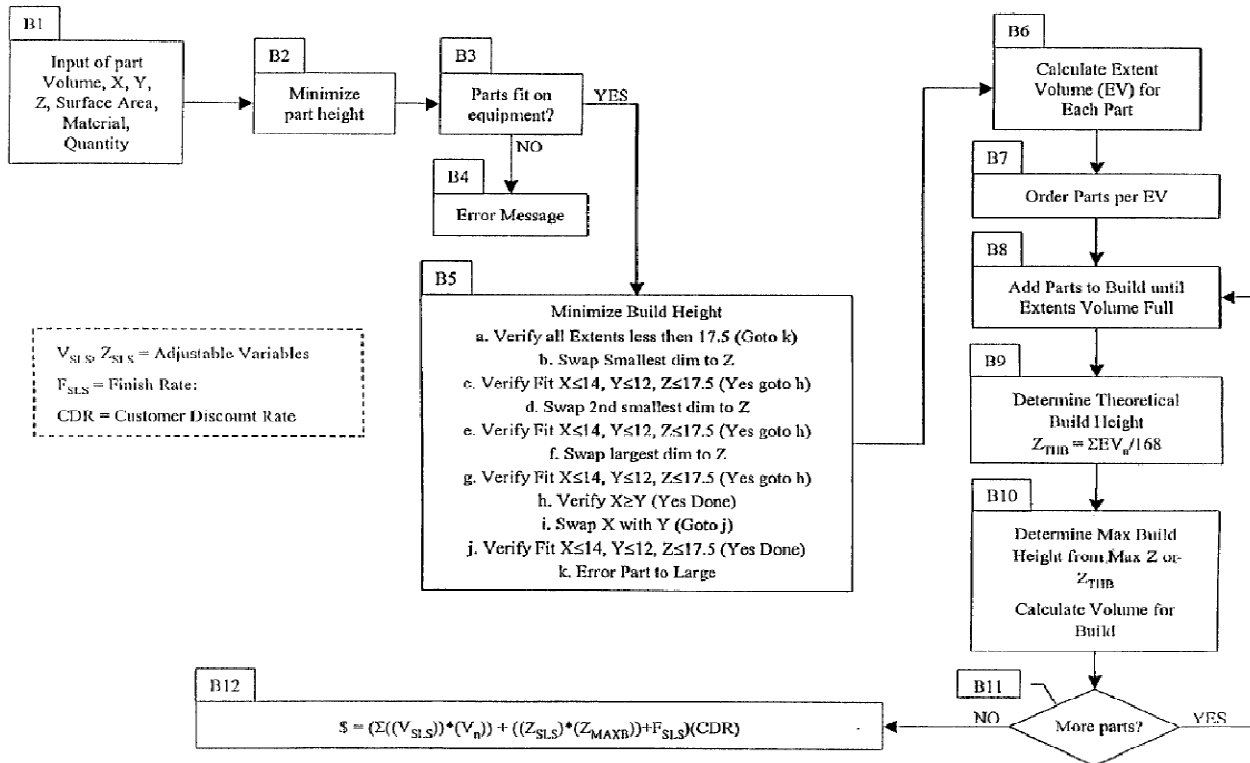
The way different service bureaus and RP/RM providers determine the cost of final part has been since long an object of discussion. The need to quote a single part with a reasonable price and profit margin is accompanied by the necessity to be compatible with external quotes made by competing centres which own the same technology but may have dissimilar operating costs. Even when parts are to be built for internal clients, i.e. design, prototyping, sales or other departments inside the same company, there's a need to control the source of expenses and the final cost.

RP and RM pricing may differ according to every centre's expenses but also due to different expected profit margins. In this battle to achieve more competitive costs one of the main factors is the speed of calculation. The term "Online quoting" refers to the prices offered mainly trough internet platforms by different RP service bureaus which through the analysis of a CAD file usually in .STL, .IGES or other compatible exchange formats, are capable of calculating the cost of a part, according to a set of characteristics assigned by the customer within the same interface (process, material type, level of finishing, post processing).

A web-based price quotation system usually follows the following steps (Hollis and Michael 2007):

- Receiving access on a server computer system from a customer computer over a global communication network;
- A pre-existing computer aided design (CAD) file describing a three-dimensional custom manufactured part originated by a customer;
- analyzing the pre-existing CAD file on the server computer system to determine one or more manufacturing criteria for the custom manufactured part;
- calculating in the server computer system a firm price quotation for the custom manufactured part based upon the one or more manufacturing criteria; and
- transmitting the price quotation to the customer computer over the global communication network.

Although each RP centre has its own “quoting formula” the quotes for a 3D CAD file, for the same process, material and machine may dramatically differ from one centre to another. Quoting systems are not usually disclosed since they comprise a competitive advantage; however a bad cost estimating system might play against the company’s interest. Recently the first patent was issued to a service bureau (Quickparts.com), Hollis and Michael (2007) who claimed a business model to online quote 3D parts made by several RM technologies. Figure 6.10 shows one the standard procedure claimed to asses the automated part costing for SLS process.



As indicated in Figure 6.10, the program accepts an STL file of the part to be built as sent by the customer. The system calculates the volume of the part, the X, Y and Z extents of the part and the surface area. Then the part is re-oriented so as to minimize the part height thus minimizing processing time. Then a series of measures are taken in order to assure the part can be built inside the build chamber of the appropriate machine. The system executes a proprietary grouping algorithm to add parts to the RP machine arranged from the largest to the smallest extent volume. Afterwards the build height is calculated as the maximum Z dimension of the tallest part or group of parts in the chamber. Once all parts have been added the system will compute costs based on equation 18:

$$\$ = ((V_{SLS}) * (V_n) + (Z_{SLS}) * (Z_{MAXB}) + F_{SLS}) * (CDR) \tag{18}$$

Where:

\$ = final cost

V<sub>n</sub> = volume of part n

Z<sub>MAXB</sub> = maximum part height

F<sub>SLS</sub> = part finishing level (as defined by the user)

CDR = customer discount rate (based on historical data from the user)

The rest of the factors namely Vs and Zs are determined by statistically regressing a number of historical pricing data against the general equation (19)

$$price = a * V + b * H + c \quad (19)$$

Where:

a, b and c are pre-programmed constants

V corresponds to the volume of the parts to be built; and

H correspond to the vertical height of the parts in the selected orientations

While online costing is a common practice for gaining clients worldwide there are more conservative centres that still rely on manual non-automated pricing which usually includes more detailed aspects of the fabrication. The main disadvantage is that the final part cost cannot be calculated with the same efficiency and can be provided only when the machine bed is fully packed, which usually happens till the end of a working day.

### 6.9 Costing methods comparison

Although the cost and time estimation systems presented herein claim to predict the RM machine output with enough accuracy to assign appropriate costs, several experts state that RM machine runtimes cannot be predicted with error levels under  $\pm 20$  percent (RP-ML 1999-2009). As the aforementioned costing models comprise different strategies for cost estimation and allocation it is of high interest to compare them in equality of conditions in order to assess their suitability to be embedded in the RMADS system.

A collection of parts has been compiled which includes 3D cad files of mechanical elements, individual parts as well as complex and shapes with intricate and extreme features. The parameters of the complete list of 130 parts can be consulted in Annex 4 along with their specifications (volume, max. height, bounding box). Some of the parts included are of the same volume and height in order to detect the sensibility of the different models to capture the geometrical complexity and translate it into cost mainly due to major or less material consumption.

Table 6.5 shows a sample of 20 parts that were randomly taken from the sample set in order to compare the methods depicted in this chapter. Since the method developed by Ruffo was specially created for a Vanguard SLS machine hence imposing a number of restrictions, the other methods have been applied with the same process and machine information so that the same conditions are used.

**Table 6.5 Methods for cost estimation (US dollars) and their corresponding error against the reference cost**

Part No.	Service bureau	Ruffo (€)	Error %	Wilson (€)	Error %	Hopkinson (€)	Error %
1	48.07	75.60	57.28	69.05	43.65	59.49	23.76
2	105.17	109.61	4.22	100.01	4.90	60.78	42.21
3	54.79	124.26	126.77	109.20	99.30	59.83	9.19
4	42.91	58.45	36.23	55.68	29.77	58.84	37.13
5	70.46	61.48	12.75	66.12	6.16	61.88	12.18
6	140.47	113.55	19.16	97.44	30.63	56.26	59.95
7	36.84	71.75	94.74	68.96	87.17	55.26	49.98
8	41.04	63.18	53.97	56.70	38.17	55.43	35.08

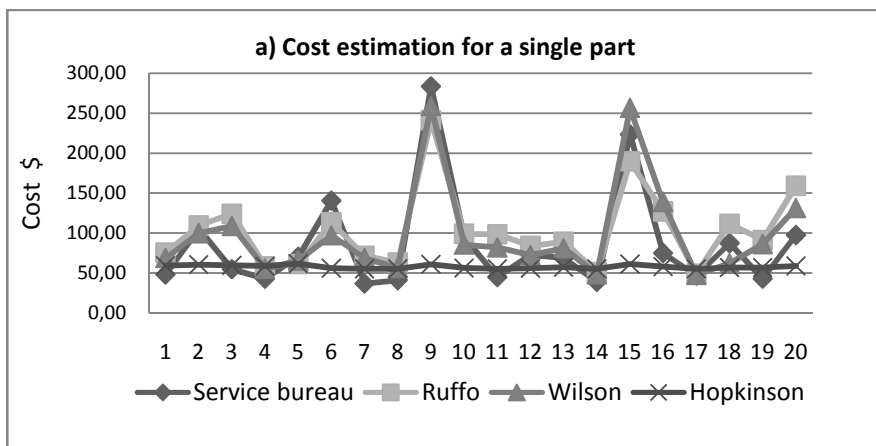


9	283.40	240.95	14.98	258.91	8.64	61.15	78.42
10	94.51	99.18	4.95	85.78	9.23	56.36	40.36
11	44.95	98.52	119.20	82.25	82.99	55.39	23.23
12	72.49	83.92	15.77	72.70	0.29	55.99	22.76
13	68.76	89.27	29.83	81.02	17.84	57.37	16.56
14	38.70	51.24	32.39	48.78	26.03	55.37	43.06
15	223.45	189.81	15.06	256.65	14.86	61.37	72.53
16	74.94	127.22	69.77	139.17	85.71	58.10	22.47
17	46.72	49.45	5.84	47.97	2.67	55.30	18.37
18	87.43	111.72	27.77	62.54	28.47	56.87	34.96
19	42.72	91.29	113.70	86.49	102.47	56.89	33.18
20	97.49	159.18	63.28	131.44	34.83	58.94	39.54
		Avg. error	45.88		37.69		35.75

The second column on Table 6.5 belongs to the price of the 20 parts as quoted by a service bureau (Materialise 2008) selected randomly from a number of available online quoting system. Service bureaus usually charge a minimum part cost of around 100 to 120\$ even if the real cost of fabrication is lower. However the price considered for this comparison is the actual part cost before applying the minimum fee. For further detail the MatLab source code for the three compared methods can be consulted in Annex 3.

It can be seen how the three methods exhibit high error rates going from 35 to 46% however in their respective sources they claimed significantly lower average error rates (from 15 to 30). An early assumption is that the source of such high error rates is the lack of a more accurate build-time estimation method. As shown in the previous section each method has its own “engine” for calculating build-time, while the cost allocation strategy followed is not quite different among the three approaches.

Figure 6.11 shows the comparative graph of the cost estimation for a single part and for batches of 10 parts for every model.



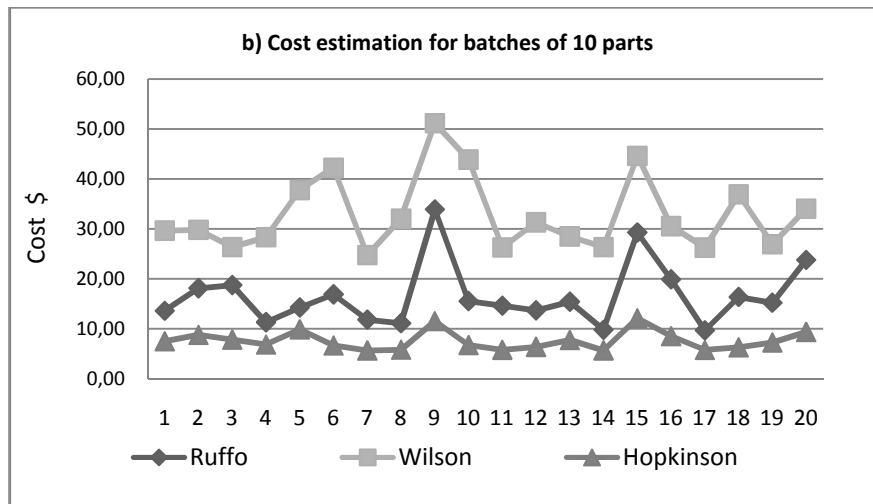


Figure 6. 11 Comparative graph of the cost estimation for a single part and for batches of 10 parts for every model

The Service bureau estimation is not considered in b) since its method does not respond to low volume manufacturing costing. On the other hand it can be seen how the three methods respond to an increase of the batch size with a corresponding reduction of the price per part. The advantages and drawbacks of using a certain method for cost estimation are not that clear however if the background of each approach is analysed one may find that the method proposed by Hopkinson is less sensible to changes in the parts geometry as seen in the previous figure, thus providing cost estimated that are proper for mass production. On the other hand, although the cost estimation provided by Wilson seems a viable solution, it takes into account machine and processing parameters that are hard to collect for every machine and process.

### 6.10 Conclusion

Although a number of parametric cost estimation techniques may be used which consider factors such as machine amortization, overhead, materials, recycling, uptime, etc. the ultimate retail cost of a given part is more a reflection of the fair market value of the service, rather than cost plus some margin value. However an early cost estimation is useful for measuring the complete advantage between adopting one manufacturing route or another and therefore it must be included since the earlier design stages. For the purpose of this work the method that best fits the desirable cost allocation criteria is the one provided by Ruffo et al. (2006) however its build-time estimation engine must be replaced by a more effective approach if it is to be used within a wider variety of Rapid Manufacturing processes. Therefore the next section goes deeper into the development of a more effective time estimation method based on Artificial Intelligence.

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