



Development of an Additive Manufacturing Decision Support System (AMDSS)

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Abstract

Additive manufacturing (AM) technology describes a set of processes capable of producing 3D physical products from CAD data directly. The rapid development of AM technologies and their wide applications makes the selection of the suitable process chains and materials a difficult task. Some researchers have tackled this problem by developing selectors that should assist users in their selections. The existing selector systems have some drawbacks: (i) often being outdated even before they were completely developed because new processes and materials are evolving continuously, (ii) representing only the point of view of their developers because users were not involved in the development process and (iii) not being holistic and able to help in all AM aspects for example process chains, materials, finishing methods and machines. This work has developed an updatable decision support system that assists users in their selections regarding AM process chains, materials, finishing methods, and machines. First, the study started by analyzing the available additive manufacturing selector systems and identifying their shortcomings. Secondly, the researcher identified target specifications for the new system, investigated different possible architectures for the system, selected knowledge based system (KBS) and database (DB) architecture to work together as a versatile tool that achieves the required target specifications. Next, the first version of the system was developed. Furthermore, verification and validation processes were made to test the developed system. Three case studies were used for the validation purpose: a typical consumer razor blade and two automotive components. These case studies were manufactured using AM technologies and then a comparison between real life decisions and the developed decision support system decisions were made. In addition, a number of interviews were performed in order to obtain users' feedback about the first developed version. As a result of the feedback and evaluation a second version of the system was developed and evaluated. The results obtained from the second evaluation suggest that the second version is more effective than the first version during the selection process. To conclude, this study has shown that using KBS and DB together is effective to develop an updatable additive manufacturing decision support system. In addition, the user involvement in the development stage of the system enhances the system performance.

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AHP	Analytical Hierarchical Process
ALM	Additive Layer Manufacturing
AM	Additive Manufacturing
AMDSS	Additive Manufacturing Decision Support System
ANP	Analytical Network Process
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
DB	Database
DLS	Direct Laser Sintering
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EDM	Electrical Discharge Machining
ES	Expert System
FDM	Fused Deposition Modeling
FL	Fuzzy Logic
GUI	Graphical User Interface
HDT	Heat Deflection Temperature
HIP	Hot Isostatic Pressing
HSM	High Speed Machining
IC	Investment Casting
IDEF0	Integration Definition Language 0
KBS	Knowledge Based System
LENS	Laser Engineering Net Shape
LM	Layer Manufacturing
LOM	Laminated Object Manufacturing
MJM	Multi-Jet Modeling
NN	Neural Network
QFD	Quality Function Deployment
RIM	Reaction Injection Molding
RM	Rapid Manufacturing

RP	Rapid Prototyping
RT	Rapid Tooling
SFFF	Solid Free Form Fabrication
SGC	Solid Ground Curing
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SMART	Simple Multi Attribute Decision Making
ST	Silicone Tooling
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UV	Ultra Violet
VC	Vacuum Casting
3DP	3D Printing

Chapter 1. Introduction

1.1 Introduction

Additive Manufacturing (AM) is defined by ASTM as the “process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing technologies such as traditional machining”(ASTM,2012).

At the beginning the aim of the new technology developed was to build prototypes quickly. The first generic name was rapid prototyping and the first process developed in the late eighties was Stereolithography (SLA). When the technology was later developed to produce tools and dies it was called rapid tooling. Finally, when it is used to produce final products it was called rapid manufacturing (Levy et al.,2003).

The technology advanced quickly and applications have widened into medical, sculpture, architecture, industrial and many others domains. Different names were given to this technology, for example free form fabrication, digital manufacturing, layer manufacturing, 3D printing, additive fabrication, additive processes, additive techniques, additive layer manufacturing and layer manufacturing (Pratt et al.,2002, Dahotre and Harimkar,2008, Choi et al.,2011, ASTM,2012). The reason for the confusion in the name is that the usage of this technology has passed over its initial purpose.

After Stereolithography was developed many technologies have evolved like: fused deposition modeling, 3D printing, selective laser sintering, selective laser melting, electron beam melting, solid ground curing and laminated object modeling. Some of these technologies are not used anymore and some are still present in the market and are progressing. AM technologies are not only used as single processes but also as part of a process chain; for example Stereolithography models and investment casting: the first mould of the investment casting process is made with SLA technology. Furthermore, most of the AM metal based processes such as laser engineering net shape (LENS), selective laser melting (SLM) and electron beam melting (EBM) are used for tooling processes to produce moulds and dies for injection moulding and die casting.

The advances in the AM technology are not only limited to new processes, but also new materials, new machines and new finishing methods. This expansion in techniques and materials has created a strong need for a system that could help and assist users in the selection of the possible process chains, materials, finishing options and machines. This need was the main motivation for this research.

1.2 Research Problem

According to Gibson (2002) there are three main problems regarding rapid prototyping that benefit from decision support system:

- Selection support. What technology and material a user should use to build a part?
- Capital investment support. What technology should a user buy to fulfill his requirements?
- Process planning support. What are the parameters that need to be controlled and what are the optimum process values that give the optimum results.

The scope of this research covers the first question. When a user has a part with specific requirements, what is the most appropriate technology and material that could fulfill the requirements of the given part.

The target users of the system are inexperienced and average users. The inexperienced users are those who start to learn and use AM technologies such as students in universities while average users are more advanced and have basic knowledge about AM technologies but they are not experts that use AM technologies on regular basis. They have a little information about some AM processes and materials. For example, design engineers that need to manufacture a part and are used to conventional processes.

The growing numbers of AM technologies and the quick advance in their processes, materials and machines make the selection of the suitable process a hard task. There are 38214 AM systems sold around the world from 1988 until 2009 (Wohlers,2010). Experts and service bureaus are the main sources of information for users that needs to select AM processes and materials.

Most users do not use constructive and formal evaluation procedures for the suitability of the AM processes and materials for a given application (Ghazy and Dalgarno,2009). In addition, the selection problem involves many alternatives and many criteria that conflict with priorities which make the selection harder (Khrais et al.,2011).

The right selection of a process is not only limited to a single process but to a complete process chain from the material to the different finishing methods that could be used. Some designers also do not include AM processes or materials because of the lack of knowledge about these technologies and their capabilities. Many designers stick to the conventional processes and materials that they know which prevents them from discovering new opportunities in new developed technologies. The development of AM technologies happened in less than twenty five years which makes them relatively new. Selectors give the opportunity to users to discover the new possibilities and new methods to produce product quickly and effectively.

When a user or a designer has a part with specific requirements such as a specific tensile strength or hardness or working temperature he needs to get an advice from an unbiased person or system. The ad-hoc technique or the previously known solutions could give users a selection that is not necessary the right one that satisfies the criteria of users. The right choice for process chains, materials and machines could be a critical element to the success of the developed product whether it is a prototype visual or functional, a tool or die, and an end-use product.

1.3 Research Aim and Objectives

1.3.1 Aim

The aim of this research is to develop an additive manufacturing decision support system (AMDSS) for inexperienced and average users that is capable of evaluating and selecting the most appropriate additive layer manufacturing processes to meet the requirements of a desired component.

1.3.2 Objectives

1. Exploring different additive manufacturing processes and examining the most up to date information about new technologies in this field, and the most widely used by industry.
2. Exploring different additive manufacturing materials, machines and finishing options.
3. Using decision analysis tools to make selection among different layer manufacturing technologies and processes.
4. Developing a system that is capable of assisting decision makers in:
 - I. Determining the feasibility of additive manufacturing processes for a particular application.
 - II. Selecting the most suitable process.
5. Testing the developed system by applying verification and validation methods.

1.4 Research Road Map

In order to develop an additive manufacturing decision support system, nine main design steps were outlined. These steps were considered a research road map. The researcher followed these steps to achieve the aim and the objectives of this research. The nine steps are:

- 1- Analyzing available additive manufacturing (AM) selector systems.
- 2- Identifying shortcomings of the available selector systems.
- 3- Identifying system target specifications.
- 4- Developing the system.
- 5- Verifying and validating the system.
- 6- Obtaining feedback from users.
- 7- Improving the system based on feedback.

8- Obtaining feedback for the improved system from users.

9- Launching the final version.

1.5 Thesis Outline

This thesis consists of eight chapters. The first chapter is this introduction. The second chapter is the literature survey which covers different additive manufacturing technologies, processes and materials. In addition, in this chapter different AM selector systems are analyzed to identify the strengths and weaknesses of each system. Chapter two discusses the first and the second design steps. The third chapter shows the development of the AMDSS. This chapter covers the third and the fourth design steps. The fourth chapter discusses the verification and validation of the developed AMDSS which is the fifth of the design steps. Chapter five describes the sixth step which was obtaining feedback from users. A questionnaire was designed to collect information and to analyze the system. Chapter six shows the development of an improved system based on feedback, which is the seventh step of the design steps. In addition, a second questionnaire was designed to collect a further feedback and obtain user's opinions about the modified and updated AMDSS. This was the eighth step. Finally, by launching the final version of the AMDSS the ninth and last step was achieved. Furthermore, chapter seven discusses the results obtained and also discusses the possible future forms of the developed AMDSS. Finally chapter eight shows conclusions and discusses future work.

Chapter 2. Literature Survey

This chapter gives an overview about additive manufacturing technologies (AM). It starts by discussing AM application areas then describes some popular AM processes, process chains and materials. The previously developed selectors are reviewed and their positives and negatives are discussed. Finally limitations of the selectors are listed and the research gap is shown. The chapter discusses the first and second of the design steps which are: 1- Analyzing available additive manufacturing (AM) selector systems and 2- Identifying shortcomings of the available selector systems.

2.1 Additive Manufacturing Overview

Additive Manufacturing (AM) is the process of producing 3D physical parts from CAD directly by adding layer upon layer of material. The main concept is to add material rather than to subtract material as in conventional machining processes (Lan,2009).

The following steps describes a basic AM process (Cheah et al.,2005, Moeskopf and Feenstra,2008) :

- 1- Creating a CAD model that represents the part that need to be built.
- 2- Converting the CAD model into STL format (standard triangulation language) which is a language that describes the part using triangles.
- 3- Slicing the STL file into cross sectional 2D layers with a specified thickness.
- 4- Generating support structures within the built part. This step is only for the processes that need support structures such as stereolithography (SLA) and fused deposition modeling (FDM).
- 5- Producing the part by adding the 2D cross section layer upon layer and repeating the layer manufacturing until the full part is fabricated.
- 6- Post processing which includes cleaning, finishing the model and removing support structures if any.

2.2 Additive Manufacturing Application Areas

AM applications can be described in three main types based on the end use for the produced parts: rapid prototyping, rapid manufacturing and rapid tooling.

2.2.1 *Rapid Prototyping*

Rapid Prototyping (RP) is using AM technology to produce prototypes. The prototypes can be used for design verification, functional testing, and marketing. It is an important part of the product development cycle that shorten product development times and lower cost (Armillotta,2006, Zhang and Liu,2009).

2.2.2 *Rapid Manufacturing*

Rapid Manufacturing (RM) is using AM technology to produce end product parts that could be used by customers directly (Hague et al.,2003, Levy et al.,2003).

2.2.3 *Rapid Tooling*

Rapid tooling (RT) is using AM technology to produce a tool or a die. RT can be divided into two main processes: direct rapid tooling and indirect rapid tooling. In direct tooling the AM technology is used directly to produce the mould or die using one of the AM machines. In indirect tooling AM technology is used to produce a pattern then the pattern is converted to a mould.

Examples of rapid tooling are patterns for sand casting and patterns for investment casting (Levy et al.,2003, Pal and Ravi,2007, Nagahanumaiah et al.,2008). Furthermore, Dippenaar and Schreve (2012) reported the use of rapid tooling in injection moulding, vacuum casting and electrical discharge machining.

Figure 2.1 shows different AM applications. Rapid prototyping (visual aids, presentation models, functional models, fit and assembly) represents 26.2% of the AM applications; rapid tooling (patterns for prototype tooling, patterns for metal castings, and tooling components) represents 56.5% of the AM applications and rapid manufacturing (direct part production) represents 15% of AM applications (Wohlers,2010).

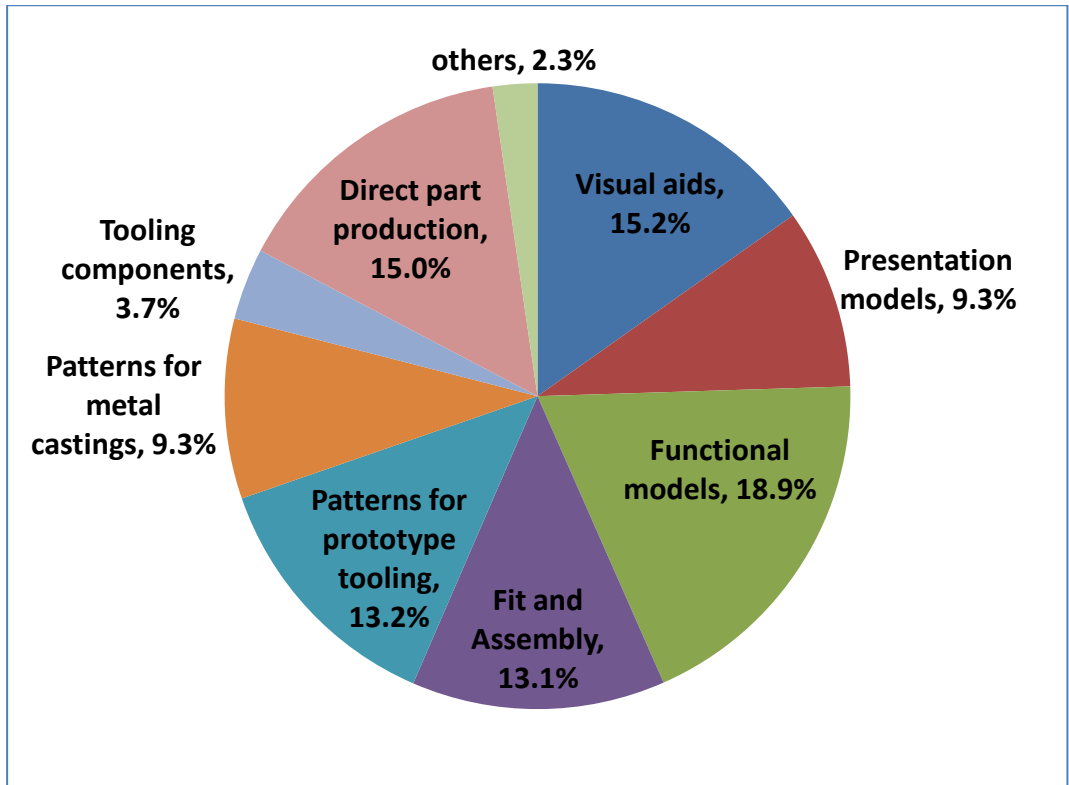


Figure 2.1: Additive Manufacturing Different Applications (Wohlers,2010)

2.3 Additive Manufacturing Processes

In 2009, there were 35 AM system manufacturers that sold 6002 machines. The number of AM systems sold increased each year. Figure 2.2 shows the number of machines sold from 2005 to 2009 (Wohlers,2010).

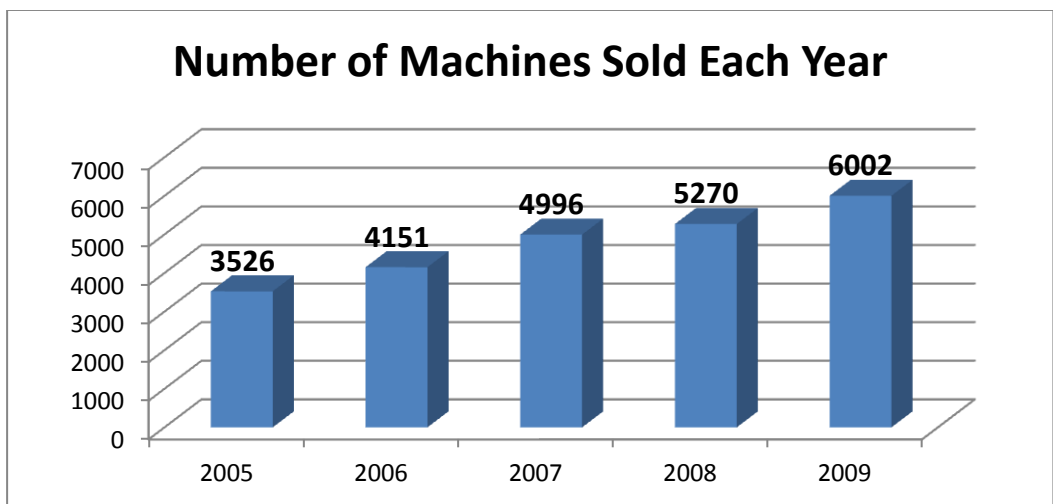


Figure 2.2: Number of AM Machines Sold Each Year (Wohlers,2010).

The system manufacturers produce different processes. There are too many developed AM processes to cover them all here. Some of the most popular AM technologies are therefore presented below.

2.3.1 Stereolithography (SLA)

Stereolithography was the first AM process introduced to the market by 3D Systems in 1987 (Hopkinson et al.,2006). SLA is based on a platform that contains vat containing a photopolymer liquid resin. An ultraviolet (UV) helium-cadmium or argon ion laser is used to solidify the resin. The 3D CAD file is sliced into a series of 2D cross section layers. Each sliced section is drawn individually onto the surface of the resin. The laser solidifies the first layer, the platform is lowered and the new layer of resin is scanned by the laser. The process is repeated many times until the model is fully grown layer by layer in the vat. Some parts need support structures, which is made by the same process, and at the same time as the main parts. When the part is built, the base plate is then raised to lift the part. The part is then drained, washed and the support structure broken away (Pham and Dimov,2003). Figure 2.3 shows a schematic of the SLA process.

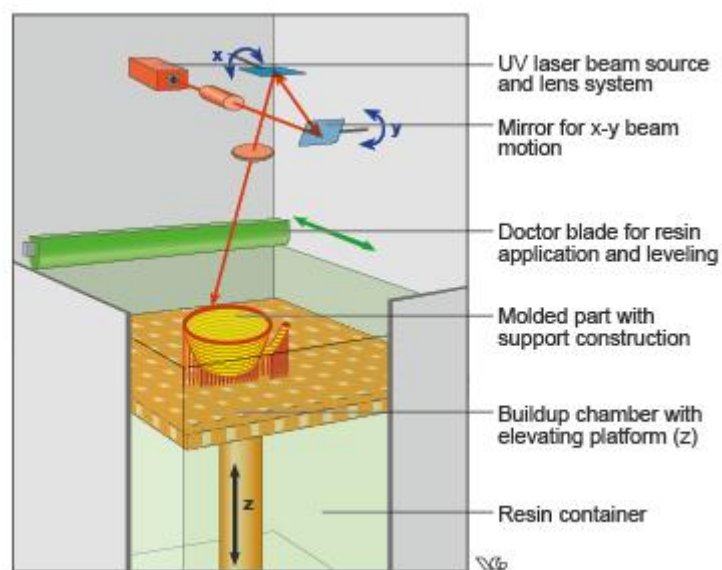


Figure 2.3: SLA Process (VG,2012).

The SLA process uses photopolymer liquid material and can also produce ceramic shapes indirectly (green part) by the photopolymerization of a light sensitive suspension such as dispersion of ceramic particles in a sensitive monomer/oligomer resin (Chartier et al.,2012, Tomeckova and Halloran,2012).

After the fabrication of the green part, a thermal treatment is applied to the part at low temperature for de-binding purpose. Next, the green part sintered with high temperature to ensure the final properties of the ceramic piece (Badev et al.,2011). The main advantage of the SLA process is that it is the superior process of all the AM processes regarding accuracy (Melchels et al.,2010).

2.3.2 Fused Deposition Modeling (FDM)

Fused Deposition Modeling is an AM process commercialized by Stratasys in 1991 (Hopkinson et al.,2006). It extrudes and deposits thermoplastic filament materials in layers on a platform. The head has two movable nozzles. The first nozzle deposits molten material and the second nozzle deposits the support material. The material is heated above its melting point so that it solidifies immediately after the extrusion (Pham and Dimov,2003). The part that needs to be built is sliced into layers, the two nozzles move together to form the first sliced layer, then the platform is lowered and then the process is repeated until the complete part is built by depositing a layer upon layer. Figure 2.4 shows a schematic of the FDM process.

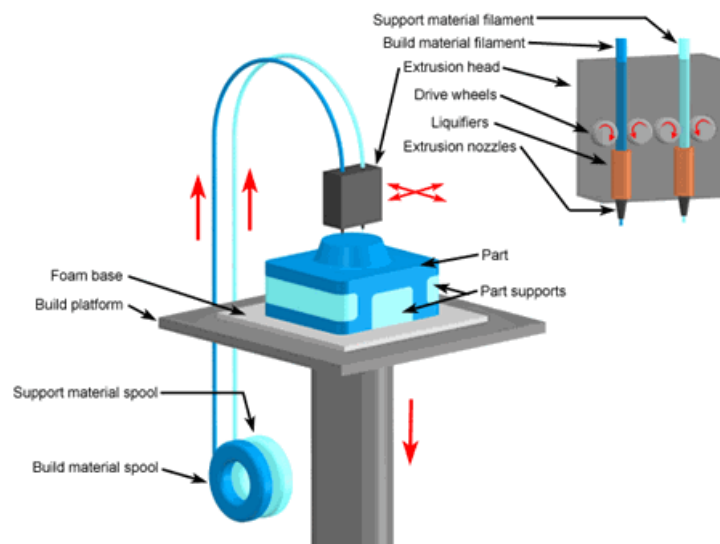


Figure 2.4: FDM Process (Custompart.net,2012).

The range of materials includes thermoplastics such as ABS and Polycarbonate, biocompatible materials and heterogeneous materials (Choia et al.,2011). The FDM process (sometimes called FDC fused deposition of ceramics when producing ceramics) has been used to produce structural ceramics and piezoelectric ceramics for incorporation into ceramic polymer directly and indirectly (Grida and Evans,2003).

The advantages of the FDM process are: it is reliable, safe and simple fabrication process, the range of materials includes many thermoplastic materials that have wide applications, and many materials used are considered low cost materials (Masood and Song,2004).

The major disadvantages of the FDM process are: parts fabricated with the process lack the isotropy of mechanical properties, are very sensitive to process parameters and the uneven heating and cooling cycles of the FDM process causes residual stresses which lowers the strength of the parts fabricated (Sood et al.,2010).

2.3.3 *Selective Laser Sintering (SLS) / Selective Laser Melting (SLM)*

Selective Laser Sintering

Selective laser sintering (SLS) and selective laser melting (SLM) are two similar powder based processes. SLS produce polymers and can produce metals indirectly while SLM produces metals directly.

Selective Laser Sintering (SLS) is an AM powder based process that was originally developed by University of Texas at Austin in USA and commercialized by a company called DTM (later acquired by 3D systems Inc) (Hanemann et al.,2006). A CO₂ laser beam fuses the material powder to form a cross section or a slice of the desired product. The entire bed is lowered and after that cylinders spread a new layer of the powder over the previously fused layer. The laser beam repeats the fusing process again and forms another new layer. Layer upon layer is deposited until a complete product is formed (Hon and Gill,2003). The sintered material forms the product while the un-sintered material remains in place for product support (Pham and Dimov,2003). Figure 2.5 shows a schematic of the SLS process.

SLS can produce polymers directly such as polyamide, glass filled polyamide, aluminum filled polyamide and carbon filled polyamide, while metals can be produced indirectly. Indirect SLS consists of two stages by sintering a polymer coated metal powder to produce a green part in the first stage. The second stage involves heating the green part in an oven and infiltration with bronze or copper to have a fully dense metal part (Levy et al.,2003, Ilyas et al.,2010). The SLS process produces ceramic parts indirectly by sintering polymer-coated ceramic powders but the parts are not fully dense (Tang et al.,2011).

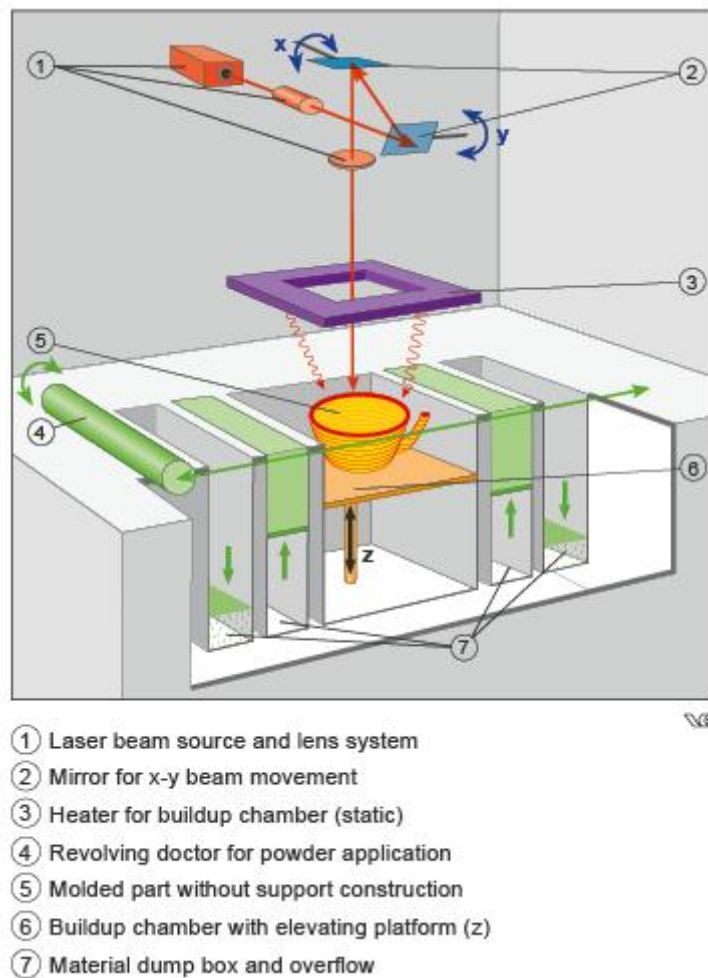


Figure 2.5: SLS Process (VG,2012).

The advantages of the SLS process are: there is no need to have support structures when building parts, so parts can be built freely in the building chamber which increases productivity and lowers cost (Soe,2012) and also the parts produced are characterized by having good mechanical properties.

Most of the materials used are highly crystalline or semi- crystalline polymers. Amorphous materials do not have a specific melting point so they are heated until

reaching the glass transition temperature but the produced parts are weak and do not have the good mechanical properties (Hopkinson et al.,2006).

Selective Laser Melting

Selective laser melting (SLM) is an AM process that is first commercialized by MTT Technologies Group of Stone since 2003. SLM have the same building technique as the SLS process except that in SLM the laser melts the powder and does not sinter it. The laser melts metal powder on a powder bed and produce parts layer upon layer. The range of materials include stainless steel, aluminum alloys, titanium and tool steel (Wohlers,2010). Fully dense parts can be produced directly by SLM (selective laser melting process) (Yves-Christian et al.,2010).The almost full density gives an advantage of yielding bulk material properties (Yasa et al.,2011).

2.3.4 3D Printing (3DP)

3D Printing (3DP™) is a powder based AM process developed at MIT. The process produces physical parts by spreading powder over the surface of a powder bed. A binder material is used to join layers together. There is a piston that lowers the powder bed after a new layer is formed so a new layer of powder can be spread as shown in Figure 2.6Figure 2.6: 3DP Process (Custompart.net,2012). Repeating this process produces the 3D physical part (MIT,2012).

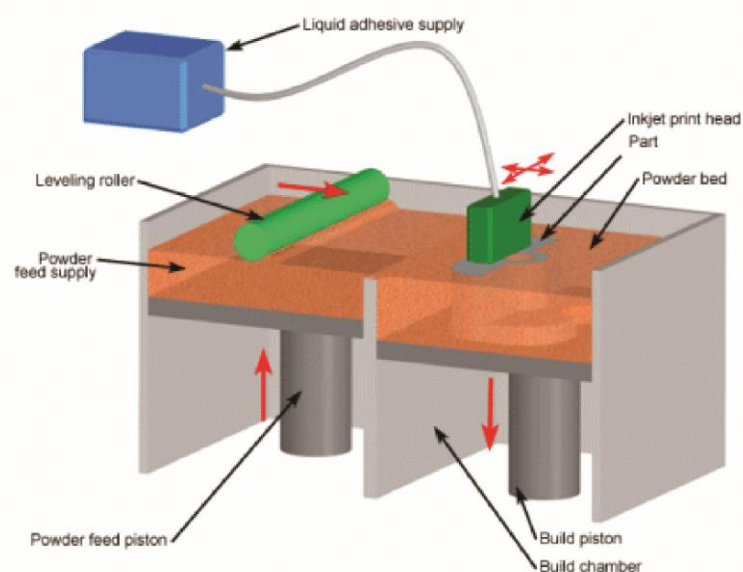


Figure 2.6: 3DP Process (Custompart.net,2012).

The 3D printing can produce porous ceramics shapes. The head eject an organic binder on ceramic powder (Parasad et al.,2006, Derby,2011). The SLA, FDM and SLS are characterized by definition around 150 μm while 3D printing can reach 50 μm (Su et al.,2008b, Noguera et al.,2005). There are some disadvantages of the ceramics parts produced by AM processes such as: 1- anisotropic shrinkage due to residual stresses arisen from polymer binder drying in printing methods or high shear field in extrusion based methods, 2- poor surface quality, 3- poor surface finish, 4- poor dimensional accuracy and 5- the stair-steps effect decreases the ceramics strength and toughness (Su et al.,2008a).

2.3.5 Ink-Jet / Multi-jet Modeling (MJM)

The ink-jet method patented by Solidscape and the multi-jet modelling (MJM) patented by 3D systems, are very similar AM processes with little differences.

Ink-Jet

In the ink-jet process the jetting head has three nozzles. The first nozzle jets the thermoplastic material while the second and the third nozzles jet the wax support material. Each layer formed is milled to a specific layer thickness. The System uses drop on demand (DOD) technology and high precision milling for each layer (Hanemann et al.,2006). Figure 2.7 shows the ink-jet process.

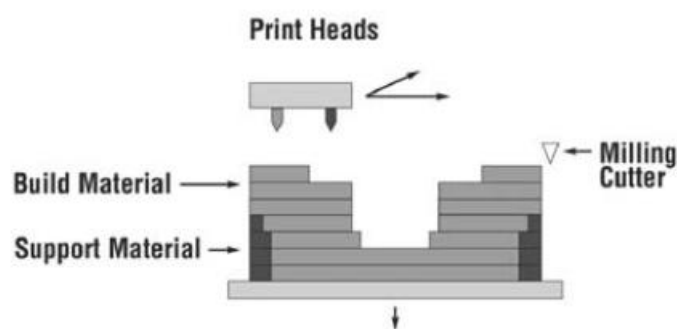


Figure 2.7: Ink-jet Process (Hanemann et al.,2006).

The advantages of the ink-jet process are: it is able to deposit materials with different chemical and physical properties, it has low operational cost (Khalate et al.,2011), position accuracy is high and production reproducibility is also high (Khalate et al.,2011).

The disadvantages of the ink-jet process is that it is low speed process, surface finish of the parts are not very good , and jetting of high temperature materials is difficult to achieve (Fathi et al.,2012).

Multi-Jet-Modeling (MJM)

In the multi-jet modeling (MJM) there is a head with multiple spray nozzles and an ultra violet (UV) lamp. The nozzles deposit tiny droplets of hot photopolymer liquid (thermopolymer) and the UV polymerizes the liquid. The process of depositing the liquid and the polymerization forms the first layer, and is repeated to form layer upon layer until the final part is made (Zemnack et al.,2007). Figure 2.8 shows the multi-jet modeling process.

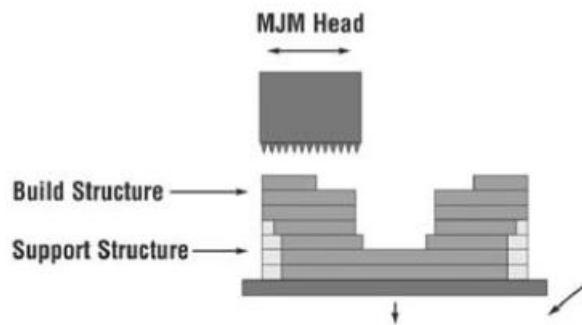


Figure 2.8: MJM Process (Hanemann et al.,2006).

2.3.6 Laser Engineering Net Shape (LENS)

Laser Engineering Net Shaping is an AM process that deposits powder and fuses it simultaneously (Pham and Dimov,2003). The LENS process was developed by Sandia National Laboratories and commercialized by Optomec Inc since 1997 (Hanemann et al.,2006). Figure 2.9 shows a schematic of the LENS process.

The head of the LENS process consists of a laser beam and two nozzles that feed coaxial powder. The process takes place in an atmospherically controlled environment usually of argon gas. First the high power laser (750-1000 w) focuses on a metal part to create a molten pool. Next, the powdered metal is supplied from the nozzles to add more volume. The table that the part is on it moves in the X-Y direction to create the first layer, while the head moves up and down in the Z direction to build the part height. The process is repeated to build a layer upon layer until the complete part is built (Amano and Rohatgi,2011).

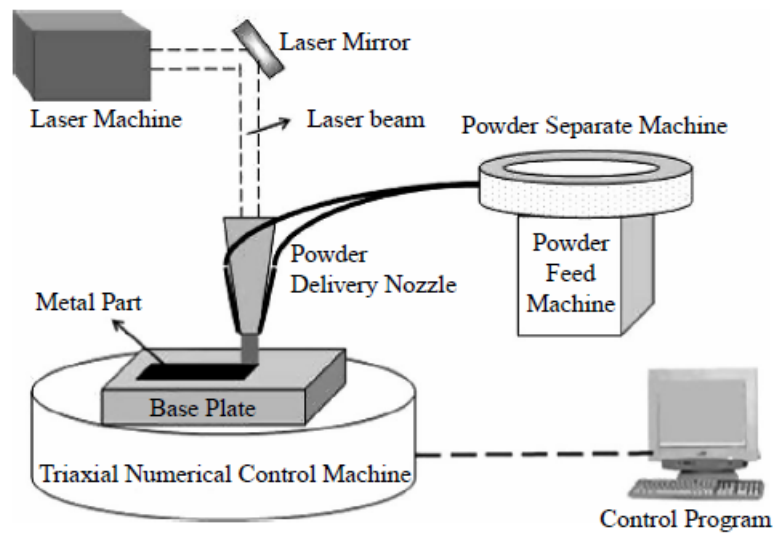


Figure 2.9: LENS Process (Zhao et al.,2009).

The LENS can process various metals such as nickel based alloys, stainless steels, tool steel, cobalt-chrome and titanium alloys. One of the advantages of the LENS process is that it can produce fully dense materials. (Wohlers,2010, Zhao et al.,2009).

2.3.7 *Electron Beam Melting (EBM)*

Electron Beam Melting is an AM process available from Arcam AB (Sweden) since about 2005 and its main concept is that electrons are generated in a gun, accelerated and focused using electromagnetic lens and electro magnetically scanned by an embedded CAD program (Murr et al.,2012).

First, a powder metal is spread over a platform. The electron beam melts the metal powder and builds the first layer of the part. Next, the platform is lowered by one layer thickness and a new layer of metal powder is spread. This process is repeated until the complete part is built by adding a layer upon layer over the platform (Lu et al.,2009). Figure 2.10 shows a schematic of the EBM process.

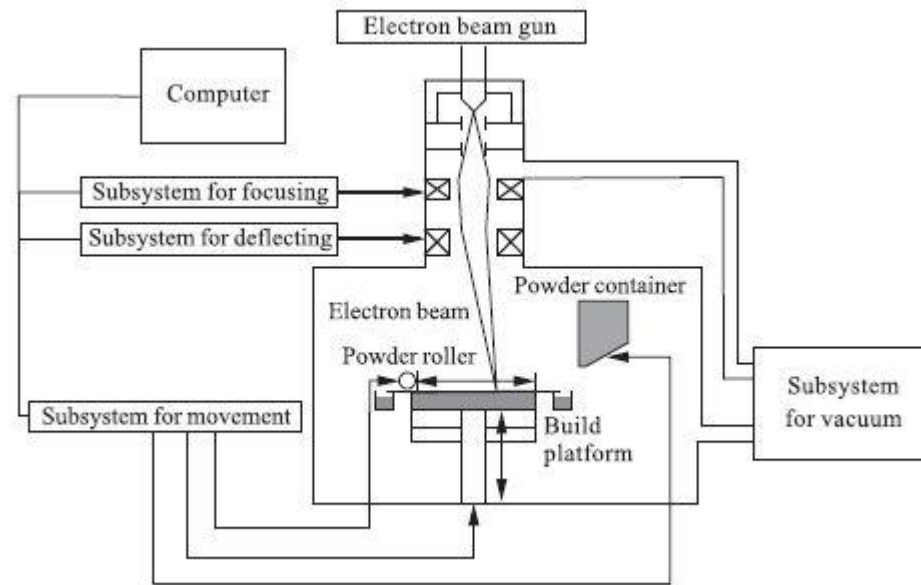


Figure 2.10: EBM Process (Lu et al.,2009).

The range of materials used by EBM process include: titanium, cobalt-chrome, titanium aluminide, inconel (625 & 718), stainless steel (e.g. 17-4), tool steel (e.g. H13), aluminum (e.g. 6061), hard metals (e.g. NiWC), copper (e.g. GRCop-84), beryllium (e.g. AlBeMet), amorphous metals, niobium and invar (Arcam,2012b).

The advantages of the EBM process is that the parts built have stable chemical composition because of the vacuum environment, excellent mechanical and physical properties because of the even temperature distribution within the part. In addition, EBM has relatively high productivity because of the high deposition rate (Arcam,2012a).

2.4 Additive Manufacturing Process Chains

2.4.1 *Rapid Tooling Process Chains*

In the literature, the AM process chain terminology is used mostly to express direct or indirect rapid tooling such as using SLA or any other AM process to create patterns for reaction injection molding, vacuum casting or investment casting. The following are some examples of rapid tooling process chains used in the industry:

i. Stereolithography + Reaction Injection Molding (SLA + RIM)

Reaction Injection Molding (RIM) is a process in which two or more low viscosity, highly reactive chemicals are mixed and injected together into a mould to produce polyurethane objects (Dias et al.,2012). The SLA process produces the mould used in the RIM process. Figure 2.11 shows a schematic of the RIM process.

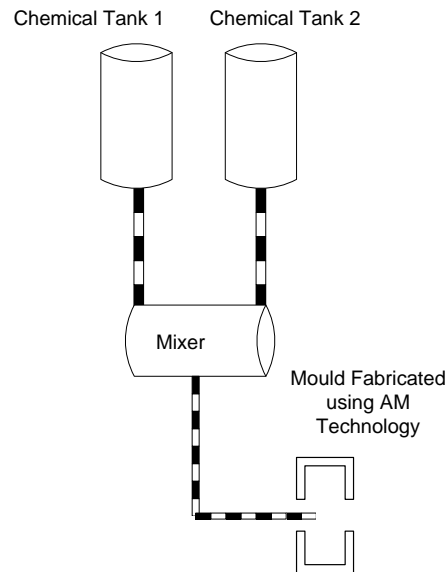


Figure 2.11: RIM Process.

The two liquid chemicals are stored in tanks. They are fed to a mix head where they are mixed together. Next, the two liquids flow from the mix head to the mould under atmospheric pressure and the chemical reaction begins. The following steps (Dias et al.,2012) describe the RIM process: 1- mixing the two low viscous liquids into a mix head, 2- filling the mould, 3- Curing and solidification of the mixture, 4- Part extraction, and 5- Post-curing to complete the solidification and improve mechanical properties of the produced part.

ii. Stereolithography + Silicone Tooling + Vacuum Casting (SLA + ST + VC)

The SLA + ST + VC process chain consists of three main steps: 1- the SLA process creates a pattern of resin material, 2- silicone is cast under vacuum around the SLA pattern to create a silicone mould and 3- the silicone mould is cured in an oven at 40°C for four to six hours. After curing, the mould is cut to create parting lines and the pattern is removed.

The silicone mould is ready for the vacuum casting process. The silicone tool is cheap and can produce complex shapes, fine patterns and deep groove and without drafting angle (Zuo,2012). Vacuum casting is used to produce parts made of metals (non-ferrous), wax and plastics (Thian et al.,2008). The process chain is used for small series from 10 to 20 parts (Chua et al.,1998, Materialise,2012). Any AM process such as SLS or FDM could replace the first step but it is more common to use SLA process in industry.

iii. Stereolithography + Investment Casting (SLA + IC)

The investment casting process is an industrial process considered as an economic approach for mass production of metal parts with complex shapes (Rahmati et al.,2009). The investment casting process is a very old industrial and the term investment refers to the slurry or investments used to produce the mould (Jones and Yuan,2003).

The traditional steps in investment casting are: 1- producing moulds, 2- producing wax patterns, 3- producing ceramic shell, 4- pattern removal 5- pre-heating and firing, 6- casting and knockout.

The SLA process can be used to produce patterns made of epoxy resin instead of the wax patterns in step number 2. There is a build style on SLA machines called QuickCast which fabricates the SLA patterns with a quasi-hollow structure. The main concept is that the hollow structures would soften at lower temperatures and collapses inward upon it-self before critical stress levels are developed. The QuickCast build style solves the problem of the difference of the coefficients of thermal expansions between the SLA patterns and the ceramic shell. The benefits is to reduce tooling cost and tooling time (Cheah et al.,2005).

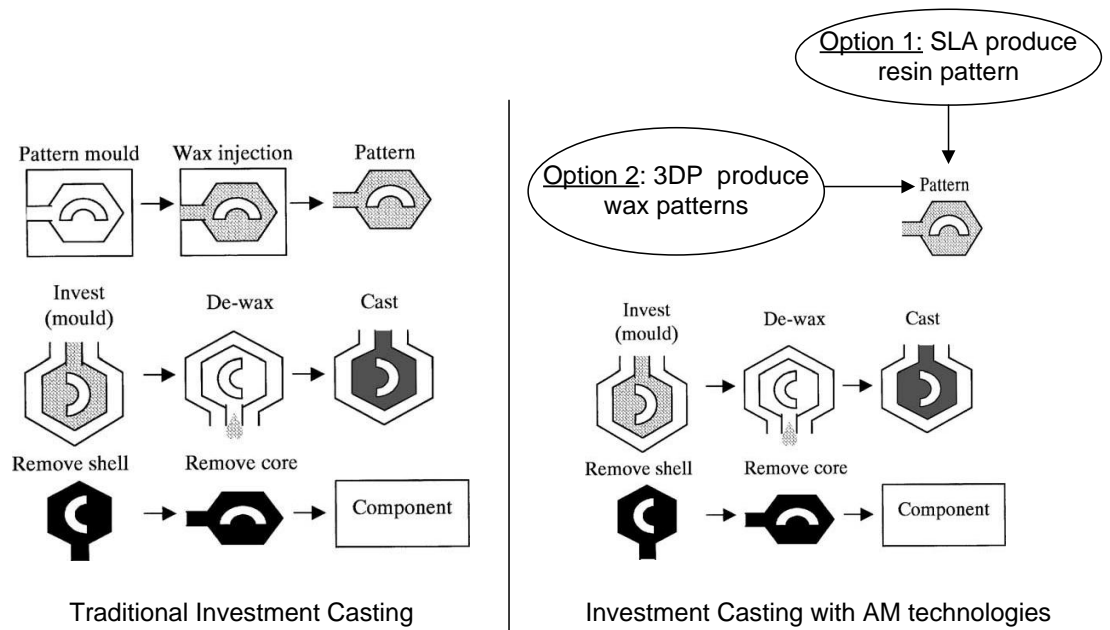


Figure 2.12: Investment Casting Process (adapted from Jones and Yuan,2003).

There are also other AM processes that could fabricate either the wax patterns or non-wax patterns for investment casting processes such as FDM, SLS and 3DP but SLA is the most successful because of its good surface finish and good dimensional accuracy (Cheah et al.,2005). Figure 2.12 shows a schematic of the traditional investment casting process and the use of AM technologies with the investment casting.

2.4.2 General AM Process chains

Although in the literature AM process chain terminology is mostly used for rapid tooling this study looks at the AM process chain terminology from a broader perspective and considers that AM process chains should have a more generalized definition: an AM process chain is any manufacturing process route that involves at least one additive manufacturing process in it. Any sequence of processes that produce a part or a tool or a prototype using an AM process and other conventional or non conventional processes, is considered an AM process chain. Figure 2.13 shows different possible AM process chains.

The first reason to justify the definition of the general AM process chain is that most of the time AM processes are not used alone to produce parts especially when the purpose is to have a functional prototype or an end use product. Secondary processes are needed for finishing like for example sanding,

machining, grinding, electroplating, polishing, sandblasting, texturing and/or combinations of them. Leong et al. (1998) have discussed the secondary process for finishing of jewellery models built using SLA such as: tumbling, filling, sanding, buffing, tapping, sawing, trimming, and grinding. Lamikiz (2007) have used laser polishing as a secondary process to improve the surface finish of a part built by an SLS process. Galantucci et al. (2009) have made chemical post treatment to improve the surface finish of ABS parts made on an FDM system.

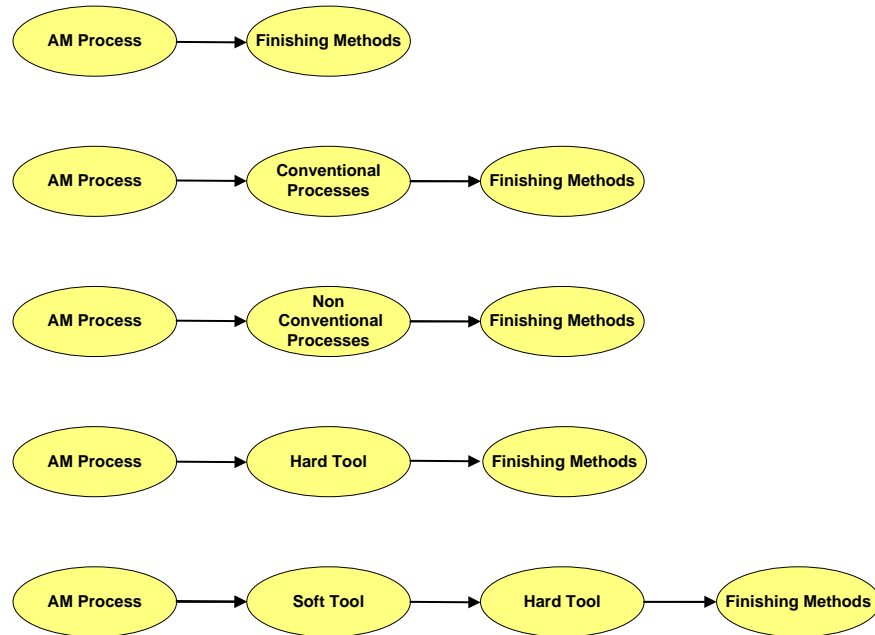


Figure 2.13: Possible AM Process Chains

The second reason is that for some applications it is better in terms of cost or time to use additive manufacturing and conventional manufacturing to manufacture one part. For example, Das et al. (1999) have fabricated a titanium sidewinder missile guidance section housing (an end-use product) using SLS/HIP (selective laser sintering and hot isostatic pressing). Mognol et al. (2007) have proposed an approach based on topological analysis of the tool and the manufacturability possibilities of the involved processes. A decision is made to manufacture different components (in the same tool) using high speed machining (HSM) or electrical discharge machining (EDM) or direct metal laser sintering (DMLS).

Although, this method is proposed for a tool there is no reason that prevents using the same method with any end-user part or a prototype. Ilyas et al. (2010) have used an AM process chain to produce an injection mould tool. The chain consists of using 1- indirect SLS process to produce the mould, 2- high speed machining

(HSM), 3- electron discharge machining (EDM) for primary finishing and secondary finishing is made by grinding and polishing.

2.5 Additive Manufacturing Selection Systems

After the development of the first rapid prototyping system SLA many other systems appeared. The advances were not limited to new technologies but also new materials. The selection of the most appropriate systems became a problem that many researchers have tackled by developing models and decision support systems.

At the beginning researchers considered this from the perspective of rapid prototyping and this later extended to rapid tooling and rapid manufacturing. Looking into literature the work done can be divided into three main groups: 1- Rapid Prototyping (RP) Selectors 2- Rapid Manufacturing (RM) Selectors and 3- Rapid Tooling (RT) Selectors.

2.5.1 *Rapid Prototyping Selectors*

The first attempt to make rapid prototyping selection was a program developed by Hornberger (1993) at Santa Clara University. The program provided educational information about rapid prototyping and guided users to select RP processes.

Campbell and Bernie (1996) developed a relational database that represented the different capabilities of various RP systems. They developed a graphical user interface that users could use to search databases on build envelope, material properties and feature tolerances. After the search is done users can query the database for actual capabilities of the RP system. This system is a search tool rather than a selection system.

Muller et al. (1996) developed a rapid prototyping system selector that helped users to find the best RP system to manufacture physical prototypes. The system was based on relational databases of available machines and materials. The developed system chose the best combinations of machines and materials to make a prototype rather than selecting the most suitable RP process based on selection criteria. They used the benefit value analysis method to evaluate machine-material combination.

Phillipson (1997) developed a decision support system called RP advisor. He used quality function deployment to identify the most important features of the RP advisor. Three selection criteria were used: time, cost and quality. The system considered six RP machines and the multi criteria optimization theory was used to find the optimal selection. The system did not consider materials. The developer made two interviews with expert users to check the system effectiveness.

Muller (1999) developed a method based on a check list to evaluate an RP process chain within a European Project called RAPTEC. He has used qualitative criteria and the RP processes were compared in pairs. This was just a method for comparison and not a complete decision system.

XU et al. (2000) compared four RP systems: SLA, SLS, FDM and LOM, through a benchmark part. They developed three generic models for surface roughness, building time and building cost. The work was only limited to the mentioned four technologies and was a benchmark study rather than a selection model. These experiments became obsolete because of the advance in the technologies and the materials.

Masood and A.Soo (2002) developed a rule-based expert system called IRIS for the selection of RP machines. The system incorporated 39 RP systems available from 21 manufacturers. When developing the system two types of questionnaire were developed. The first questionnaire was for the vendors to collect information about system features, prices and applications. From 21 vendors the responses was about 70% around 15 vendors. The second questionnaire was for system's users asking about selection criteria, applications and the performance of the machines. From 136 users the responses was about 13% around 18 users. An updated version of the IRIS was developed by Masood and Al-Alawi (2002). The new version included 57 machines from 22 vendors. In the second version, users were able to update the databases using MS Access. The developers commented that the developed system needs to be always updated. The developed system was a system that aid users to select the best machines to buy rather than to select a process to suit specific application. It did not consider material selection.

Mahesh et al. (2003) proposed applying the six sigma approach towards benchmarking of RP processes by assessing process capability against its potential. They mention three types of benchmarks: geometrical, mechanical and

process benchmarks. The authors suggested that benchmarks can be stored in a database that a decision support system could use it. They developed a case study on DMLS. Finally, the paper outlined a basic web-based decision support system that included the RP benchmarking and standardization database. This work was only for DMLS process.

Byun and Lee (2005) developed a model that help users in the selection of rapid prototyping process using a modified TOPSIS ranking method (Technique for Order Preference by Similarity to Ideal Solution). The problem was considered as multiple attribute decision making. The model considered six criteria which were dimensional accuracy, surface finish, tensile strength, elongation, part cost and build time. A questionnaire was designed to ask different users about the most important selection criteria. Fuzzy numbers were used for part cost and build time. A case study reported a comparison of six RP systems. The developed model is a model that selects machines only and not processes.

Lan et al. (2005) developed new method to select the most appropriate rapid prototyping system by integrating expert system and fuzzy synthetic evaluation. An expert system was used for selection and fuzzy method was used for ranking. The developed system consists of four modules which are: 1- knowledge based expert system, 2- fuzzy synthetic evaluation, 3- databases, 4- user interface and expert interface. This paper focused on the fuzzy syntactic evaluation and did not explain the four modules of the whole system. The ranking of the alternatives (six alternatives were considered: SLA, LOM, FDM, SLS, 3DP, and SGC) was made using fuzzy AHP (analytical hierarchal process). The criteria considered were dimension accuracy, surface roughness, maximum dimension, part complexity, mechanical strength, heat resistance, running cost, post-processing cost, material cost, equipment cost, scan speed, overhead time and post processing time. The system selects only rapid prototyping processes. One of the limitations of this model is that it did not include material selection. In addition, AHP method is difficult to apply if the alternatives become very large (more than seven) or the alternatives are heterogeneous (Giner-Santonja et al.,2012) .

Rao and Padmanabhan (2007) developed an RP process selection methodology using graph theory and a matrix approach. The method gave each RP process an index obtained from an RP process function which is calculated based on a RP

process attributes digraph. A digraph is a set of nodes and a set of directed arrows where the nodes represent the RP attributes and the directed arrows represent the importance of these attributes. The arrows are directed from the more important attribute to the less important attribute. The ranking was done according to the calculated index. The considered attributes were: dimensional accuracy, surface finish, type of material, material properties, part cost, build envelope, range of layer thickness, part size, feature type, feature size, ease of use, and environmental affinity.

The authors used the case study reported by Byun and Lee (2005) who developed the modified TOPSIS method. A comparison between the two models showed that the graph theory and matrix approach is better than the modified TOPSIS because it can enable more critical analysis since any number of attributes quantitative or qualitative can be taken into consideration. The limitations of this method are that the selection is for machines and not processes. In addition it is only a decision model, cannot be updatable and is complex for novice users.

2.5.2 *Rapid Manufacturing Selectors*

Bernard (1999) and Bernard et al. (2003) discussed the development of an expert system using CAPP expert system called ACPIR (aided choice for rapid industrialization processes). The developed expert system was not only for layer manufacturing machine selection but it was designed to be more general looking at the product development integrating: CAD, reverse engineering and indirect methods for metallic and plastic parts manufacturing. The developed system contained two types of reasoning: 1- case based reasoning which uses old case studies stored in the system to predict similar solution to similar problems, 2- bottom-up generation of a process where the system suggested solution for the user based on the knowledge using the expert system rules. The case based reasoning is used first and if a solution is not found the bottom-up approach is used. The limitations of this system are that users cannot update the system by themselves because the logic of the expert system would have to be changed. In addition, the case studies need to be updated so the case based reasoning would remain useful. Furthermore, the system included only processes and topology of materials. The material selection was not covered in a useful manner.

Bernard et al. (2003) also thought that managing the knowledge inside the database and developing a semi-automatic system for the selection is the main challenge for researchers developing decision support system for the selection of new technologies and materials in AM field.

Swedish Researchers at Industrial Research and Development Corporation, IVF (2005) also developed an online selector called RP selector. The selector asked three main questions about material/function, quantity and end-user requirements. The program was intended to aid designers and novel additive manufacturing users in:

- Giving fast, direct access to a great amount of information about practical AM based methods.
- An easy-to-learn, easy-to-use guide for novel users.
- A base for user-oriented training.
- A support for common understanding at internal and external discussions
- A communication link for information about methods, materials and suppliers of products and services.

The advantages of this system are: it is an online system, it contains good information about some of the AM processes, it considers AM process chains and not only AM machines, and it considers rapid prototyping, rapid tooling and rapid manufacturing. On the other hand, the limitations of the system are: it has a limited material database, users cannot update the system by any means and it does not rank any process or material but it gives the user different choices that the user has to trade off between.

An RM selector was also developed at Georgia Institute of Technology in 2005. The main concepts around the selector can be found in Gibson et al. (2010). It is a preliminary expert system that has been developed using Matlab environment tool that selects feasible processes and machines, it includes qualitative assessments based on several questions asking about shape similarity across production volume, part geometric complexity, part consolidation and delivery time, it

separates feasible and unfeasible machines based on material, surface finish and accuracy requirements. In addition, build time and cost can be estimated.

The advantages of the software are that: it enables users to explore AM technologies, identify candidate material, explore build times, explore the life cycles of AM products, select appropriate AM technology, explore case studies, and update machine database. In addition, it supports quotation and capital investment decisions. The main limitations of the RM selector are: it focuses on machine selection rather than process chain selection and no appropriate material selection is provided, only material exploration.

Mahesh et al. (2005) developed a system which is called IRPDMS (integrated rapid prototyping decision making system) based on fuzzy decision making and benchmarking for selecting the most appropriate rapid prototyping and manufacturing systems and they implemented it as a web page using fuzzy if-then rules. The developed web page is not available for use, only the design of the webpage is provided. The developed system interacts with a previously developed benchmark database in Wong et al. (2002) and its methodology consists of three stages: 1- representation of the decision problem, 2- fuzzy set evaluation of goals and constraints, 3- selection of the best solution. The limitations of the system are: it considered only five RP process: SLA, SLS, FDM, LOM and DLS, the system is based on benchmarking of a single part and it cannot be used as a generic approach, no material selection is mentioned and updatability is not considered.

Smith and Rennie (2008) developed an additive layer manufacturing selector tool for direct manufacturing called RM selector. The system consists of relational databases that contain information about AM machines, materials, technologies and the characteristics of parts created with a combination of machines and materials. The RM selector is a web based program that searches the databases. The limitation of the RM selector is that it is mainly a search tool rather than a process or material selection. In addition, no ranking is available.

Munguia et al. (2010) has developed an AI based system called RMADS (Rapid manufacturing advice system) which is a rapid prototyping and rapid manufacturing selection system that integrates three modules: expert system, fuzzy interface and databases.

There are three databases: process parameters, machines and materials. Users have the ability to use the material database by itself separately. Finally the fuzzy interface is used for aggregation and ranking. In his PhD thesis Munguia (2009) presented a parametric model for cost estimation and a neural network model was developed for cost estimation based on building time. One of the advantages of the system is that it can select processes and materials in a user friendly manner. Despite the system versatility it does not come without limitations: it selects process only and not process chains, updating cannot be done without changing the programming logic and users cannot make updates by themselves, and the parametric cost model is an estimate at best.

In July 2010 a new project funded within the FP7 framework called KARMA was launched (KARMA,2010).

According to Petrovic et al. (2011) the project aimed to establish an online KBE system capable of :

- Guiding users to choose the most appropriate technology, material and build scenarios.
- Offering a full mechanical and thermal characterization with emphasis on part anisotropy.
- Doing efficient process planning.

The project is ongoing and the project team does its own mechanical property experiments instead of depending on vendors' information. For 4 technologies and 8 materials 1216 tests have been made until 2011. The project incorporates only four types of technology which are: SLM, SLS, SLA and EBM. The KBE architecture is able to include more technologies.

2.5.3 *Rapid Tooling Selectors*

Durr and Kaschka (1998) have developed a method for examining and selecting conventional technologies, RP technologies and hybrid technologies. The selection criteria used are: type of part, material, purpose of the product, geometrical complexity, size of the part, dimensional accuracy, surface quality, and number of pieces. They have used a two step methodology:

1- recommendation of the most suitable process. 2- ranking according to the weighted values of quality, time, cost and ecology. One advantage of this methodology is that it considers the additive manufacturing process chains and not the technologies only. The limitations to this method are: there is no material selection and there is no possibility of updating.

Hermann and Allen (1999) have developed a rapid tooling test bed to select the most feasible process and material combination for the development of injection molding. Pairs of alternatives from each selection problem (process selection and material selection) are evaluated simultaneously. The method used is called a coupled selection-selection decision support problem. The study focused on the creation of injection molds with SLA.

The key criteria used for process selection is cost, detail capability, accuracy and build time. The key criteria used for material selection are: availability, density, elastic modulus, tensile strength, elongation and heat deflection temperature. One advantage of this test bed is the selection and the ranking of the process and material together.

Bibb (1999) developed a rapid prototyping selection system using an expert system that is composed of knowledge base and inference engine. The system selects rapid prototyping and rapid tooling technologies. It contained two types of rules: decision rules and calculation rules. The criteria used were required accuracy and minimum wall thickness. The decision rules select the most suitable RP system and the secondary tooling while the calculation rules estimated build time and build cost. The system has been verified after it has been developed by trials of seven novice users and one expert user giving their opinions regarding ease of use, usefulness of the results, and validity of the results. The system does not help in material selection. The knowledge base can be updated but not by the user because the update will need to update the logic of the expert system.

Kascha and Auerbach (2000) developed a software system called Protocol based on the methodology developed by Durr and Kaschka (1998). An expert system containing 180 rules was developed to select process chains. The expert system takes the data from technological databases that contain process chains, process steps, materials and machines.

The databases could be updated but user cannot modify it without changing the logic of the expert system.

Hanumaiah et al. (2006) developed a QFD-AHP methodology to select the rapid hard tooling process. The methodology consists of three phases: 1- prioritizing the tool requirements using AHP, 2- the results of the AHP are used as weights in QFD for selecting the most suitable tooling process, and 3- QFD is used again to identify critical process parameters. The methodology was applied to two industrial examples for validation. The limitation of this method is that it did not include material selection. In addition, no software was developed for selection.

Pal et al. (2007) developed an integrated methodology combining quality function deployment method (QFD) and analytical network process (ANP) method to determine the engineering requirements of a cast part based on the customer needs for selecting the rapid tooling processes. A case study was represented using five RP processes which are: thermo jet printing, FDM, LOM, SLA and SLA QuickCast method. The limitations to this methodology are that it did not consider material selection and depending on the pair wise comparison which will be complicated and frustrating to users if the number of the processes increases.

Pal and B.Ravi (2007) developed a database containing RT process capabilities covering 20 different rapid tooling routes, both direct and indirect. The selection of the RT route was made based on the methods developed by Pal et al. (2007). A compatibility index had been calculated and the ranking was done according to this index. The RT method with highest index is the most suitable RT process. In addition, process planning was carried using case based reasoning to find a similar process plan. There is no indication that users can update the databases. In addition the selector is limited to sand casting and investment casting only.

Armillota (2007) developed an AHP decision model (analytical hierarchical process) within a computer based tool. The AHP method is a method used for ranking by a score resulting from the composition of priorities at different levels. The model selects rapid prototyping and rapid tooling techniques. The model considered sixteen alternatives and eleven selection attributes which are: compliance to office environment, high build speed, low setup operations, availability of functional or high strength material, good dimensional and geometrical accuracy, good surface finish, economical processing, low cost

materials, low cost system usage and low setup cost. One of the limitations of this model is that updating the model by adding more processes requires that users perform pair wise comparison between all the alternatives again. Furthermore, no material selection is reported.

Hanumaiah et al. (2007) developed a fuzzy-AHP methodology to evaluate the manufacturability of the rapid tooling processes. It is based on three aspects: 1- mould feature manufacturability, 2- secondary elements compatibility and 3- cost effectiveness. A feature based database has been developed containing geometry compatibility, dimension accuracy and surface finish. Selection between six tooling processes was used for methodology validation. These are conventional tooling, SLA, SLS, DMLS, SLA+ Investment casting and spray metal tool. The database contained only information about these six tooling processes. No software development is reported in this paper.

Hanumaiah et al. (2008) developed a system for selection of rapid tooling processes and manufacturability evaluation for injection moulding. The QFD method was used for process capability mapping against asset of tooling requirements. The tooling requirements were prioritized using AHP. The manufacturability evaluation was carried using fuzzy-AHP found in Hanumaiah et al. (2007). Finally, RT cost was calculated and compared to conventional moulds. The system is only limited to injection moulds parts and there is no material selection.

Khrais et al. (2011) have used fuzzy if-then rules to select rapid prototyping techniques. They have named four methods: 1- Prototyping, 2- Investment casting, 3- Sand Casting, 4- Plastic moulding. The selection method did not deal with rapid manufacturing or rapid tooling. The selection criteria were in two groups: 1- static (does not depend on a particular application) and 2- dynamic (varies from an application to another). The advantage of this model is that fuzzy rules can deal with qualitative and quantitative variables. The disadvantage is that it cannot be updated without changing the fuzzy rules. Table 2-1 shows a summary of selector systems that is capable of selecting RP, RM and RT.

Year	System	Developers	RP	RM	RT	Process Selection	Material Selection	Machine Selection
1993	RP program	Hornberger	✓			✓		
1996	Database of RP Systems	Campbell & Bernie	✓				✓	✓
1996	RP system selector	Muller et al.	✓				✓	✓
1997	RP Advisor	Phillipson	✓					✓
1999	ACPIR	Bernard et al.	✓	✓	✓	✓		✓
1999	Rapid Tooling Testbed	Herman & Allen			✓	✓	✓	
1999	Rapid Prototyping Design Advice System	Bibb et al.	✓		✓	✓		
2000	Protool	Kascha & Auerbach			✓	✓	✓	✓
2002	IRIS	Masood & Soo	✓					✓
2005	Decision Support System for RP Selection	Lan et al.	✓			✓		✓
2005	RP Selector	IVF (Sweden)	✓	✓	✓	✓	✓	✓
2005	RM Selector	Georgia Institute of Technology	✓	✓		✓		✓
2005	IRPDMS	Mahesh et al.	✓	✓		✓		✓
2007	RT databases	Pal & Ravi			✓	✓		
2007	Computer Aided RT Selection	Hanumaiah et al.			✓	✓		
2008	RM Selector	Smith & Rennie	✓	✓			✓	✓
2010	RMADS	Munguia et al.	✓	✓		✓	✓	
2010	KARMA	FP7 Project	✓	✓		✓	✓	✓

Table 2-1: Different Attempts for Additive Manufacturing Selection.

2.6 Limitations of the Developed Selectors

The following is the summary of the limitations of the developed selectors:

- In the literature as seen in Table 2-1 most of the developed selectors are for a specific type like RP selection or RT selection or RM selection. Some researchers developed selectors that are capable of selecting two types like RP and RT selectors or RP and RM Selectors. There are only two selectors that could be classified as general selectors that are capable of selecting the three types together: 1- ACPIR expert system developed by Bernard (1999) and Bernard et al.(2003) and 2- The RP selector developed by IVF in Sweden (2005). The ACPIR was a general product development not only for AM manufacturing but it lacks material selection and updatability and the RP selector is like a general guide more than a selection tool, which does not rate the alternatives.
- Although many developed systems have used relational databases that could be updated and modified but updating the databases would require changes in the programming logic of the system.
- There is no integrated selector system that includes of the process chains, materials, finishing methods and machines all together.
- No developed systems give reasons or explanation when the system cannot give users an advice about their products.
- None of the selector systems had reported the involvement of the users in the development stages of the system. Some researchers took the opinion of expert users after the development for validation purpose only.
- Despite the selection of a process affects the selection of material and vice versa, many developed systems rank the processes or the materials alone.

2.7 Research Opportunities

The need for a study that assesses AM processes in their current state and their potential to fabricate end user products is presented by Laoui (2010). He presented an approach for developing knowledge based environment for rapid manufacturing technology and emphasized that the knowledge base should

contain process capabilities, machines, heuristic knowledge and a database that contains all the AM materials.

The limitations of the previously developed selectors open the door for research opportunities based on non fulfilled needs of users. The following is a summary of the key points that should be covered by new selectors to fulfill the needs of users:

- There is a need for a general additive manufacturing system that could help users to select rapid prototyping, rapid tooling and rapid manufacturing. The focus of the AM selector should be on the product to be produced not the technology and not the process. This product could be one part or several parts or a tool. The AM selector should take the requirements of a user for a given part and the required quantities of this part and give the user a guided selection for his application.
- There is a need to have system that could be updated by users without changing the programming logic. Most of the systems are obsolete after a while because they can only be updated by their developers.
- When a user has a part that he needs to manufacture he needs to look for materials, manufacturing processes, finishing methods and machines. There is a need to have an integrated system that helps users in the selection of the materials, process chains, finishing methods and machines. In addition, many developed systems select technologies or processes. There is a need to select AM process chains.
- Giving reasons to users if the system fails to give them an appropriate advice to manufacture their parts, consequently users can compromise and trade off between their objectives by relaxing some of the constraints to get the part made.
- Involving users by obtaining their opinions and feedback will help to create a robust system that represents the point view of users.
- There is a need for a system that is capable of ranking the processes and materials together so users can compare the rank of different materials for the same process or vice versa.

Chapter 3. Additive Manufacturing Decision Support System (AMDSS) Initial Development

This chapter presents the initial development of the Additive Manufacturing Decision Support System (AMDSS). First, it starts with the system design describing the basic steps used to develop the system and discussing the different proposed system architectures and explaining which architecture is selected. Secondly, it shows a general overview that outlines the framework of the selected architecture. This chapter explains the third and fourth steps of the AMDSS development.

3.1 Identifying System Target Specifications

The target specifications are:

1. Selecting the possible AM processes chains, materials, finishing methods and machines.
2. Giving reasons if the system could not give a solution and available AM processes or materials in the database cannot satisfy the user's requirements.
3. Ranking processes and materials according to the user's criteria
4. Ability of being updated. Users can update processes, materials, finishing methods and machines without the need to make changes in the AMDSS logic or programming.
5. Ability of being customized. The user can change and edit in the database the processes, materials, finishing methods and machines that he needs to show in the final ranking.
6. Being simple, usable, customer focused and interactive helping the user to understand the decision process step by step.
7. Being product focused, means that the selection is based on the final product requirements that the customer need to use at the end.

3.2 Developing the System

When developing the AMDSS different system architectures were considered. These architectures are explained in detail below.

1- Neural Network (NN)

Neural network (NN) architecture works on the principle of developing certain relationships between some inputs and their results as outputs. The input-output relationships maybe defined in the form of rules or patterns. The user trains the network and the NN learns the relationship between the inputs and the outputs. Based on the learned patterns, the NN can predict an output for a new input. The relationships between inputs and outputs remain hidden. For this reason neural network is considered a black box model (Vouk et al.,2011).

The neural network consists of neurons organized in layers as seen in Figure 3.1. The input Layer contains the input variables, the output layer contains the output variable (s) and the hidden layer is the place where the calculations are done. NN can have more than one hidden layer (Lu et al.,2012).

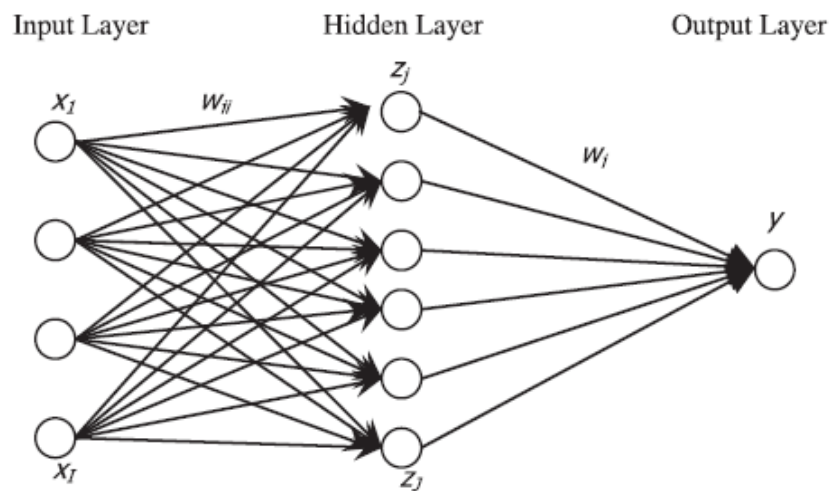


Figure 3.1: Schematic Diagram of Neural Network (Lu et al.,2012)

The first idea for the system development was to develop a neural network (NN) by using different case studies with known inputs and outputs to train the network until there was a small error percentage. The problem with this architecture is that the neural network is a black box, so the end user of the system cannot know or understand why a specific selection is made. In addition, to update the neural network the developer re-trains it by using new inputs and outputs.

This method makes the end user incapable of updating it without specific knowledge of the neural network logic.

2- Fuzzy Logic (FL)

The Fuzzy set theory was a concept developed by Lotfi Zadeh (Zadeh,1965) to look at the data as a partial set of membership rather than crisp values or non membership. Fuzzy logic (FL) is a problem solving methodology that uses vague information. The main concept is that the human reasoning uses knowledge that does not conform to precise boundaries. FL is determined by using linguistic variables like good/bad, low/high. The membership function is a graphical representation of the magnitude of participation of each input in fuzzy logic (Olugu and Wong,2012).

The second idea for the system development was to develop a fuzzy logic (FL) system that contains all the fuzzy rules so the user can have an output when entering different fuzzy inputs for the different variables. The fuzzy rules use fuzzy inputs and fuzzy outputs to describe knowledge or information. The first problem is that some inputs are not fuzzy, so representing these inputs with fuzzy variables is not realistic. The second problem is that the fuzzy rules cannot be updated by the user; it has to be updated by the developer by defining new fuzzy rules for new AM systems and materials. Consequently, the system will become obsolete after a while.

3- Expert System (ES)

Expert system (ES) is an interactive program that contains knowledge acquired from experts and helps users using the previously stored knowledge to solve complex problems. An Expert system is considered as one type of knowledge based systems (KBS). Information in the expert system is represented in the form of If-Then rules called production rules. The expert system applies the stored rules to a given data to reach a certain conclusion (Chen et al.,2012, Sahin et al.,2012). There are two types of reasoning in expert systems forward chaining and backward chaining. Forward chaining starts with data and ends with a goal or a conclusion while backward chaining starts with a goal and moves backward until finding suitable data for the desired goal.

The third idea for the system development was to develop an expert system that contains expert data regarding the selection process. The main problem encountered was that the expert system can only deal with the cases already it has the solution for, but not any new data. The user could not update the system. If there is new information, or new systems, or new materials the system cannot handle it without developer update. The developer must update the rules to include new data. An expert system would be an obsolete system in a short period because of the quick development of the additive manufacturing technologies, materials and applications around the world.

4- Knowledge based system (KBS) and database (DB)

Knowledge based systems (KBS) are computer systems that imitate human problem solving methods using a combination of artificial intelligence and knowledge base. The KBS consists of three main components: 1- knowledge base (KB), 2- inference engine (IE) and 3- graphical user interface (GUI). The knowledge base contains the knowledge used to solve problems, the inference engine derives answers from the knowledge base and the graphical user interface communicates with users taking inputs and showing outputs (Lai et al.,2011). KBS can perform knowledge management, reasoning, explanation and decision support (Li et al.,2011). Sometimes KBS and ES are used interchangeably to represent the same term but this is not precise as mentioned in (Freiberg et al.,2012). The KBS is the broader term that contains expert system as one type of it. The types of KBS could include: expert systems, case based reasoning, genetic algorithms, intelligent agents and data mining (Kendal and Creen,2007).

A database is a structured collection of data or records stored in tables with relationship in a computer program. It could be queried to retrieve information (Lai et al.,2011).

The fourth idea was to develop an integrated system that consists of a knowledge based system (KBS) and database. The KBS contains flexible rules (If –Then) which use variables and not constant values. Each time the user use the system, the variables are defined. The KBS retrieves the data from the database depending on the value of the variables decided by the user. The KBS queries the database and retrieves the information and gives it to the user.

The user can also update and customize the database, which is a key advantage. The flexibility of the IF-Then rules (using variables) gives a further advantage that the system could be updated easily by the user without changing the programming of the developed system. Furthermore, it is a step by step system where the user understands why selection is made and also the reasons why a selection cannot be made. Figure 3.2 shows a comparison between KBS architecture and KBS + database architecture. The KBS architecture is a fixed inflexible system in which the user deals only with what the developer had previously fed into the system. The database embedded in the KBS architecture is used to express the knowledge base that contains the fixed rules and fixed expertise, while in the KBS + database architecture, the database is used to express the information such as records of process chains, materials and machines. The KBS gets the inputs from the user, sends queries to the database, retrieves the information and gets back to the user with the outputs. The user can update the database directly which gives this architecture a good advantage. Consequently, the knowledge based system (KBS) and database (DB) architecture was selected because it can achieve the system target specifications explained in section 3.1.

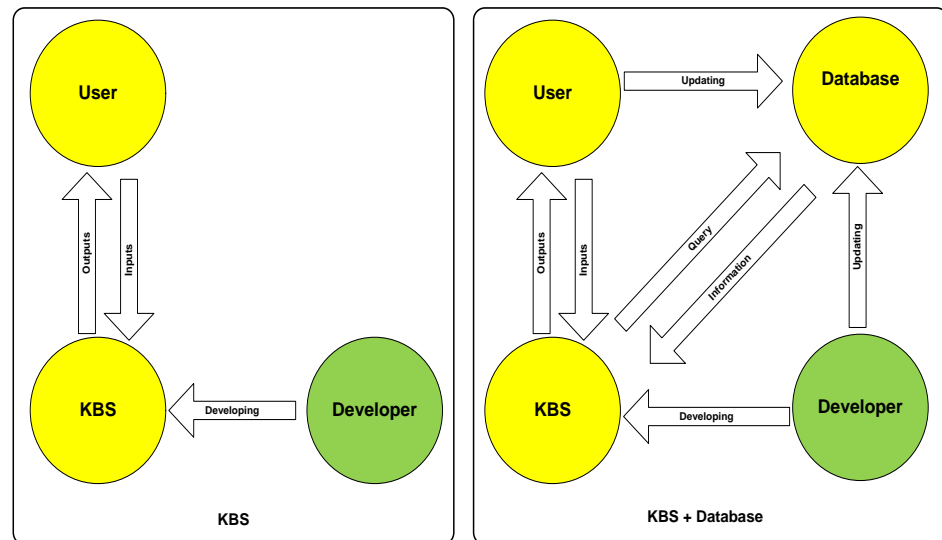


Figure 3.2: Comparison between KBS and KBS + Database Architectures.

3.3 AMDSS General Overview

The AMDSS was developed in the Matlab environment (MathWorks, Matlab version R2009b) by applying knowledge based system decision rules to select from database (Microsoft Access Database) using the database tool box embedded in Matlab. Figure 3.3 shows the AMDSS main structure. The AMDSS consists of

three main components: 1- graphical user interface (GUI), 2- knowledge based system (KBS) and 3- database (DB).

The KBS consists of three main parts: 1- selection, 2- browse and 3- update. The selection part assists users in the selection of the appropriate process according to their criteria. The browse part helps users to explore the processes and or the materials present in the database. The update part is where users can update the database with the new materials, processes, finishing methods, intermediate materials and machines.

The selection part of the KBS consists of six main elements which are: 1- process selection, 2- material selection, 3- ranking, 4- intermediate material selection, 5- finishing options selection and 6- machine selection.

The database component within the AMDSS contains five main tables: - process table, 2- material table, 3- finishing table, 4- intermediate material table and 5- machine table.

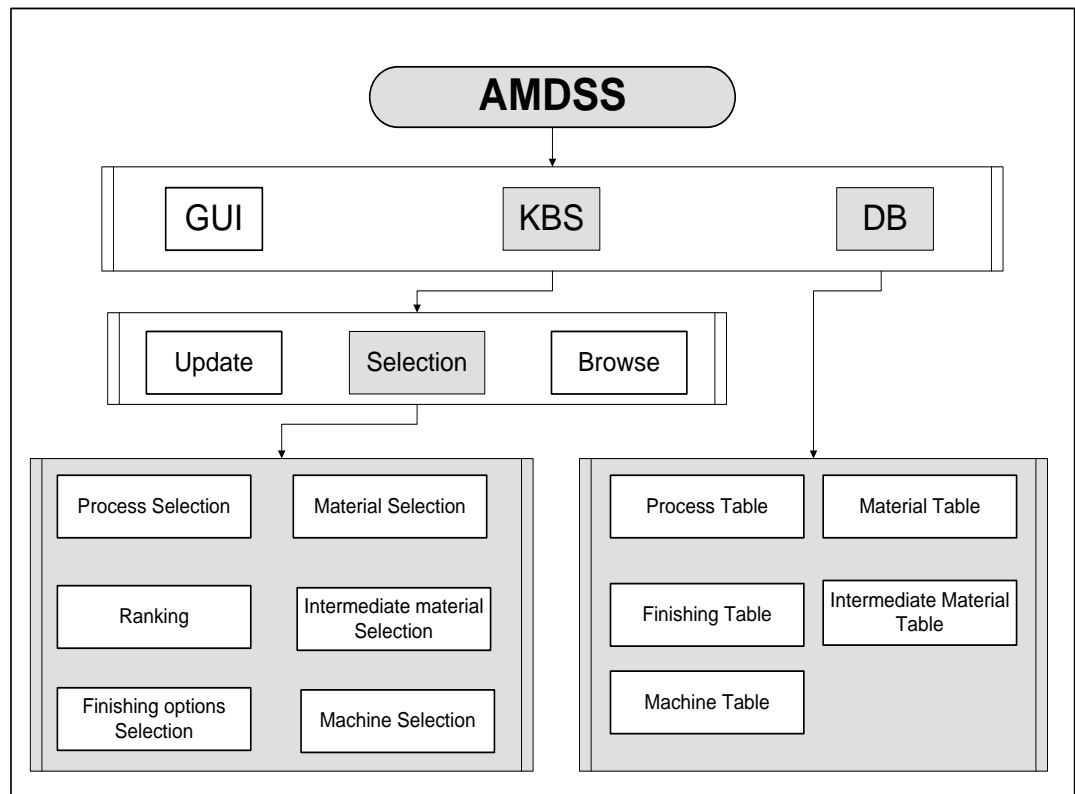


Figure 3.3: AMDSS Main Structure.

The selection part in the KBS consists of two main phases: feasibility phase and selection phase (Ghazy and Dalgarno,2011). Figure 3.4 shows the general framework of the selection part of the KBS.

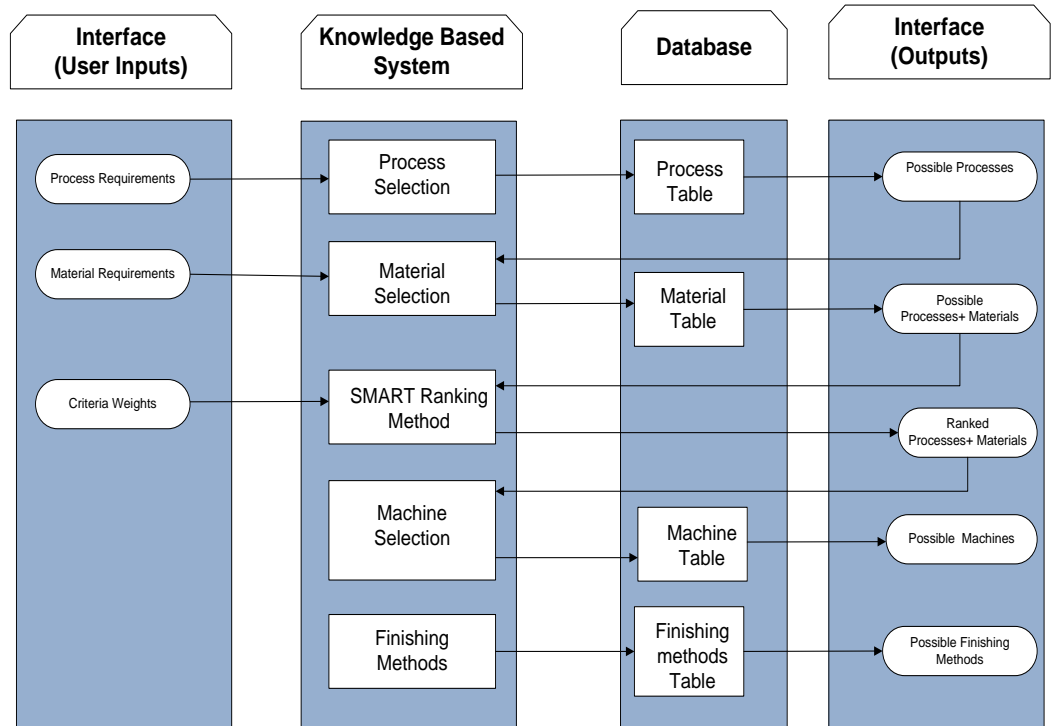


Figure 3.4: General Framework of the Selection Part of the KBS.

Phase 1: Feasibility Phase

The first phase is the additive manufacturing feasibility phase, and is done in two steps:

The first step is a process filtering step, in which the user decides on the part requirements like size, quantity, surface finish, minimum wall thickness and accuracy level. The output of this step is the possible processes that could meet the part requirements or if the part requirements are not feasible, the reasons why the part cannot be made with additive manufacturing processes. The KBS connects to database, queries them and gets the processes that satisfy these requirements The AMDSS provides also capability analysis to clearly understand the gap between part process requirements and capabilities.

The second step is a material filtering step, in which the user can select among different material properties including general properties like density and colour, mechanical properties like strength, hardness, and tensile modulus, electrical properties like dielectric strength, thermal properties like heat deflection

temperature and heat resistance, and finally environment conditions like sanitary conditions (medical consideration) and water resistance. The output of this step is the possible materials that can do the job within the selected processes in step one or if there is no materials that can meet all the requirements the reasons why the part cannot be made using one of the available materials.

The AMDSS provides also capability analysis to clearly understand the gap between part material requirements and capabilities.

Phase 2: Selection Phase

The second phase is the selection phase, in which the user with the aid of the AMDSS selects the suitable processes and materials based on the user criteria. Furthermore, user selects intermediate materials, finishing options and machines.

It starts by the user weighting some criteria by giving a scale from 1 to 10 with ten representing very important and one represents not important. The nine criteria used are:

- Strength
- Hardness
- Heat deflection temperature
- Density
- Dielectric strength
- Modulus
- Wall thickness
- Accuracy
- Surface finish

The AMDSS uses a method called SMART (Simple Multi Attribute Rating Technique) developed by Edwards in 1977 (Edwards and Barron,1994) to rank the processes and materials according to the weights of the criteria selected. The ranking value is obtained simply as the weighted algebraic mean of the utility values associated with it (Edwards and Barron,1994).

SMART was selected as a ranking method because it is simple, flexible, can be applied easily and most importantly because adding new alternatives to the method does not affect the old alternatives (unlike pair-wise comparison methods such as analytical hierarchy process (AHP) that needs that users make the pair-wise comparison each time a new alternative is added). The method was used in the AMDSS to rank different processes and materials together. Adding new alternatives such as processes and materials could be done without the need to change the programming logic which helps to make the developed system updatable as required in the target specifications.

3.3.1 Graphical User Interface

The graphical user interface (GUI) was the first component of the developed AMDSS. The user uses the GUI to send data and receives information to and from the KBS. Figure 3.5 shows the first screen that appears when the AMDSS starts. The screen has three panels.

- The first panel is the selection panel and contains one button called selection module. It is used to select the process, material, machines, finishing options and intermediate material. When this button is pressed a window screen of the part requirements opens. Figure 3.12 shows the window screen.
- The second panel is the browse panel and contains two buttons called specific material module and specific process module. It is used to browse the database for a specific process or a specific material.
- The third panel is the update panel and contains five buttons called add a process, add a material, add an intermediate material, add a machine, and add a finishing process. It is used to update the process, material, intermediate materials, machines and finishing options.

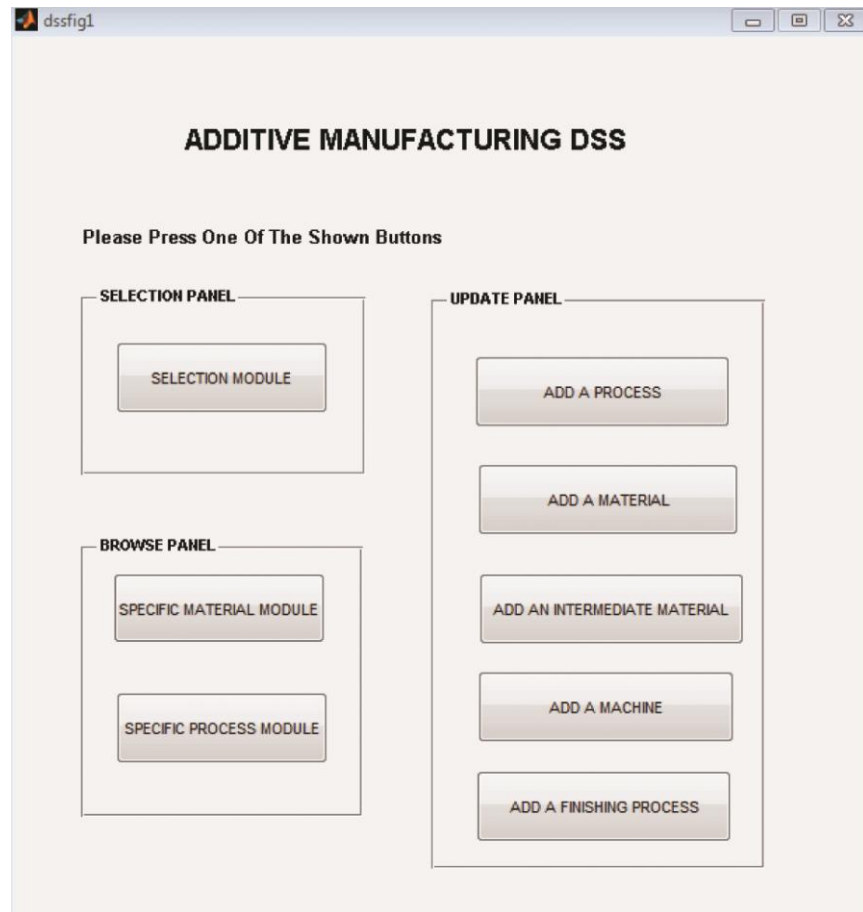


Figure 3.5: Start Screen of the Developed AMDSS.

To understand the relation between the KBS and the GUI, the selection GUI figures are demonstrated in the next section.

3.3.2 *Knowledge Based System*

Knowledge Based System (KBS) is the second component of the developed AMDSS and is composed of three parts: selection, browse and update. The following sections describe them in detail.

1. Selection part

The KBS selection part consists of six elements which are: the process chain selection element, the material selection element, the ranking element, the finishing options element, the intermediate material selection element and the machines options element. The selection part within the KBS is the core part of the AMDSS. For this reason, an IDEF0 model and flowcharts are used to describe how the selection process is made. Despite the versatility of the IDEF0 to express and explain the development of systems it does not contain decision diagrams. To

overcome this, flowcharts are also used alongside the IDEF0 models in the explaining of the system development.

IDEF0 Model Development for the Selection Part of AMDSS

IDEF is an Integration computer-aided manufacturing DEFinition language that consists of a set of re-engineering techniques developed by the American Air Force to facilitate manufacturing automation. Following a structured system analysis methodology, the IDEF methods supply a powerful means of analysis and development of systems (IDEF,2012). The selection part of the AMDSS was analyzed using IDEF0 (Integration DEFinition language 0) method within the IDEF family, which is used for functional or activity modeling of a wide variety of automated and non-automated systems for existing and non-existing systems (Kappes,1997).

IDEF0 is used here to describe every function performed within the selection part of the KBS and to whatever detail needed for each function as illustrated by the IDEF0 node diagram in Figure 3.6. Table 3-1 shows the IDEF0 node index.

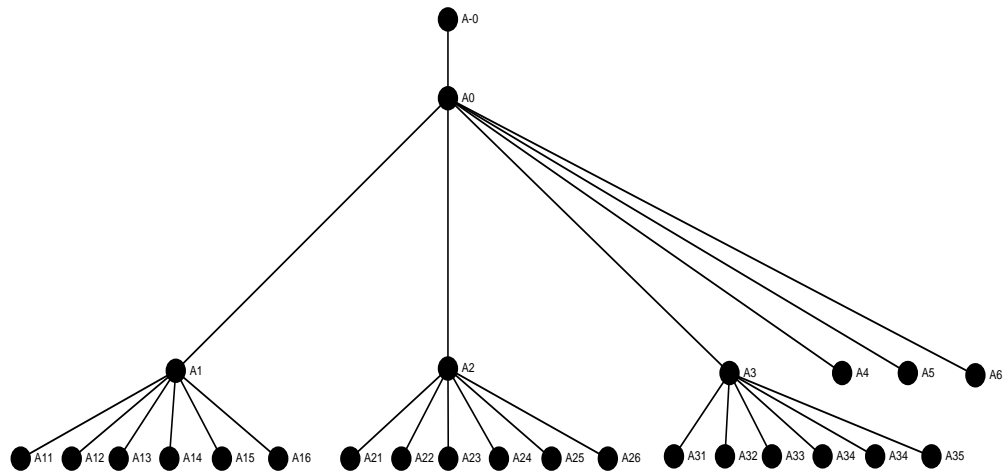


Figure 3.6: IDEF0 Node Tree Diagram

The A-0 diagram shown in Figure 3.7 is the top-level context diagram, on which the subject of the model is represented by a single box with its bounding arrows. This diagram, which is “develop an additive manufacturing decision support system”, represents the basic and main function of the model. Figure 3.8 represents the A0 diagram which shows the main steps of the selection part of the

KBS. The intermediate materials are the materials used when there is an AM process chain consisting of different stages. The possible material in step two (check possible materials for the selected processes) is the final part material, while the intermediate materials are the materials used in the different process stages before the final stage. Figure 3.9 shows the A1 diagram which checks the additive manufacturing possible process steps. Figure 3.10 represents A2 diagram which checks possible materials for the possible processes. Figure 3.11 shows the A3 diagram which is: rank using SMART methods.

A0 Develop an Additive Manufacturing Decision Support System (AMDSS)

A-0 Main Steps of the Selection Part of the KBS

A1 Check AM possible processes

- A11 Connect to the database and get the processes that satisfy minimum wall thickness.
- A12 Connect to the database and get the processes that satisfy minimum accuracy.
- A13 Connect to the database and get the processes that satisfy minimum quantity.
- A14 Connect to the database and get the processes that satisfy minimum surface finish.
- A15 Connect to the database and get the processes that satisfy the required dimensions.
- A16 Intersect all process lists.

A2 Check possible materials for the possible processes

- A21 Connect to the database and get all the material that satisfy the general properties.
- A22 Connect to the database and get all the material that satisfy the mechanical properties.
- A23 Connect to the database and get all the material that satisfy the electrical properties.
- A24 Connect to the database and get all the material that satisfy the thermal properties.
- A25 Connect to the database and get all the material that satisfy the environmental properties.
- A26 intersect all material lists.

A3 Rank using SMART method

- A31 Enter the weights of each criterion from 1 to 10.
- A32 Normalize the weights.
- A32 Divide each alternative score value by the maximum alternative score value for each criterion and multiply by 10.
- A34 Multiply normalized score values by the normalized weights.
- A35 Sum the weighted score values for each alternative and sort.

A4 Check possible machines

A5 Check possible finishing methods

Table 3-1: IDEF0 Node Tree Index

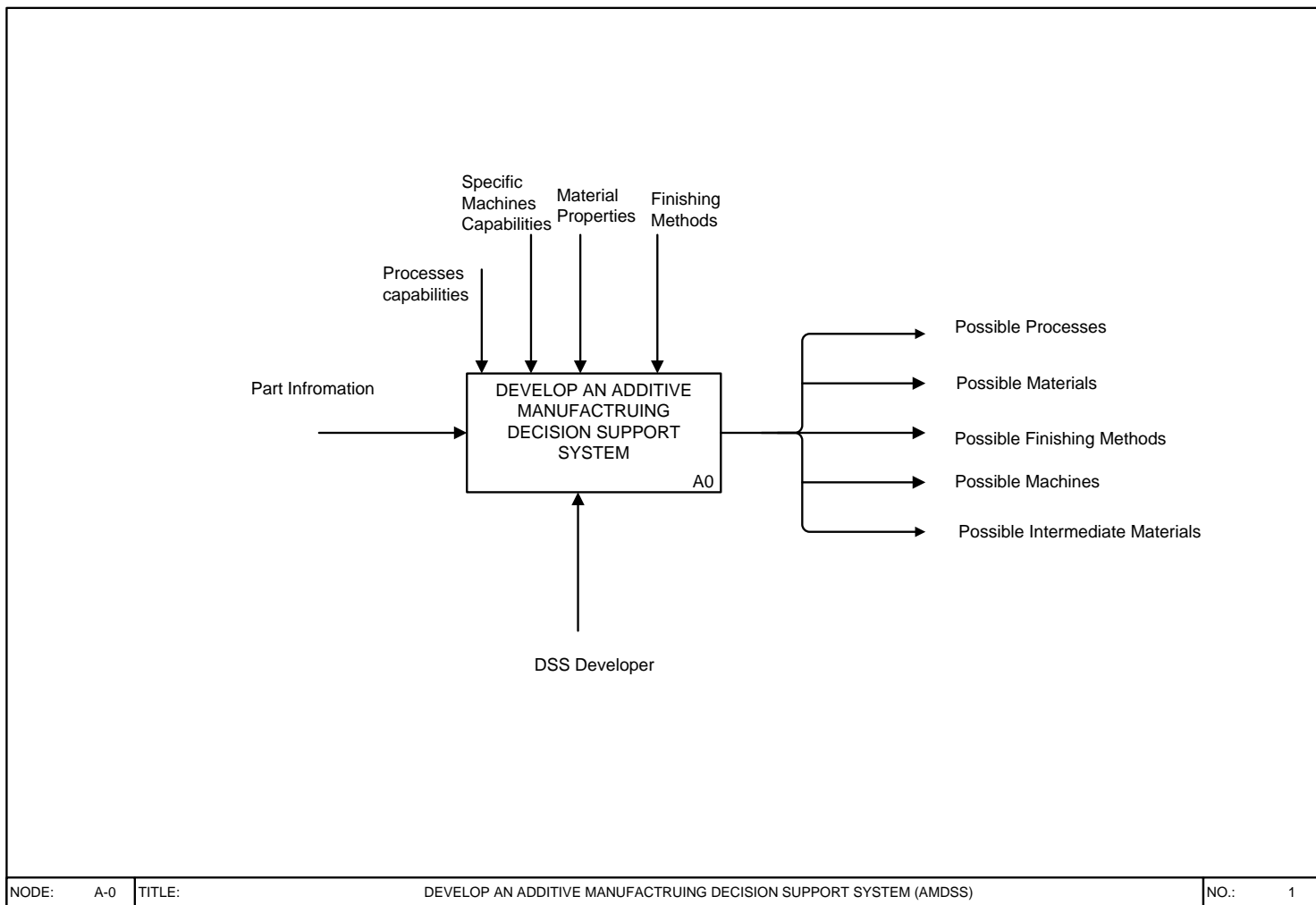


Figure 3.7: A-0, Develop an Additive Manufacturing Decision Support System.

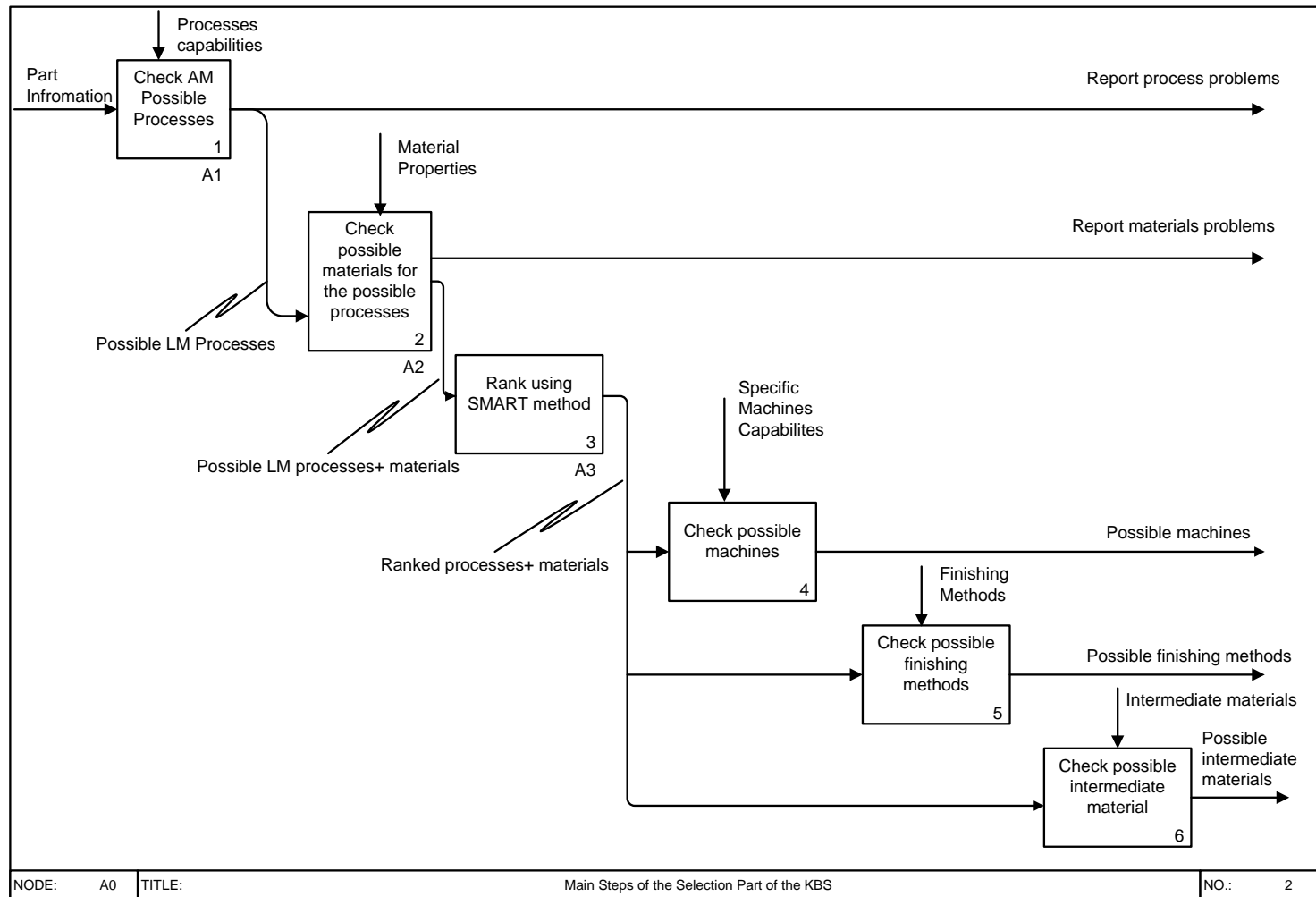


Figure 3.8: A0, Main Steps of the Selection Part of the KBS.

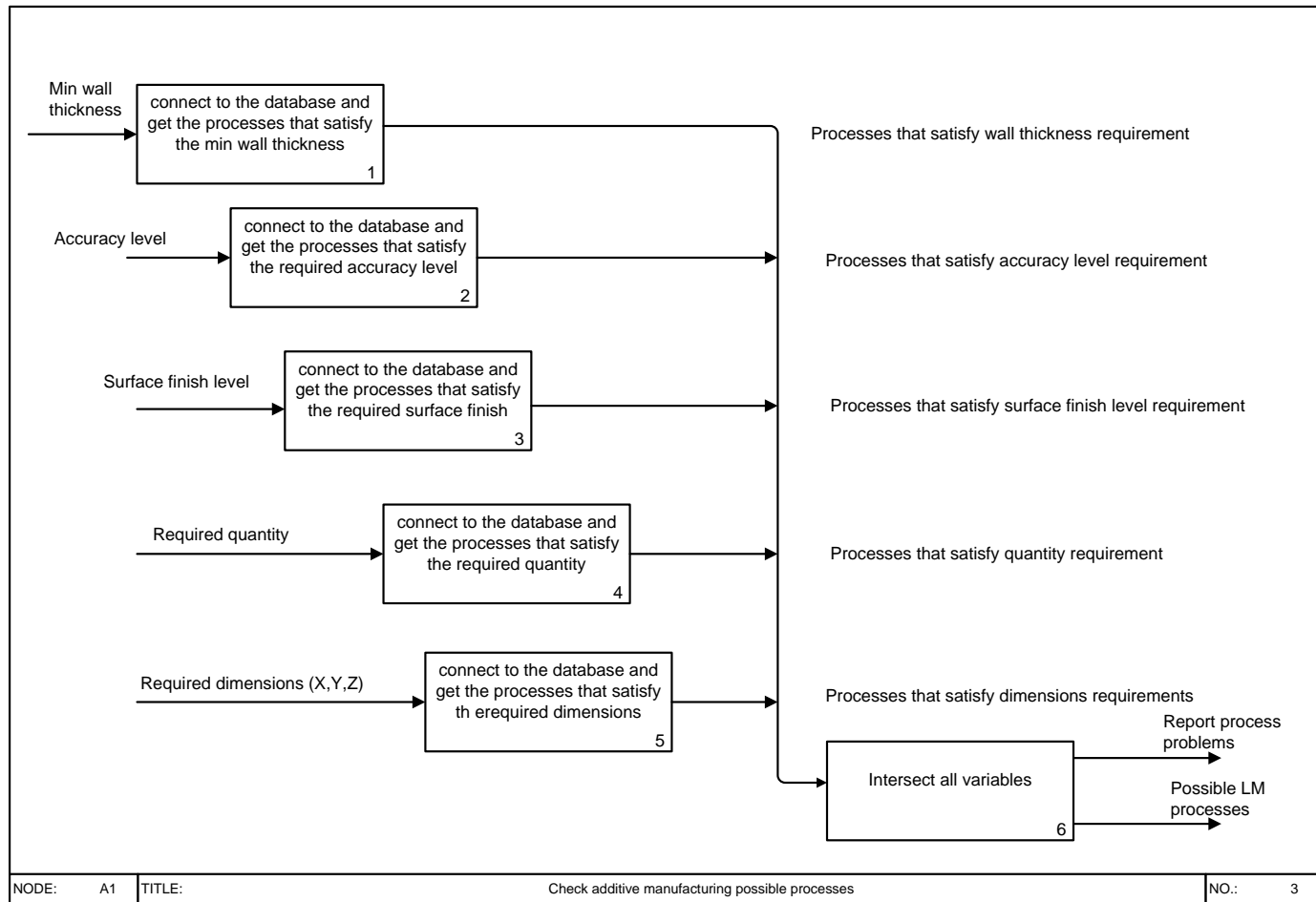


Figure 3.9: A1, Check Additive Manufacturing Possible Processes.

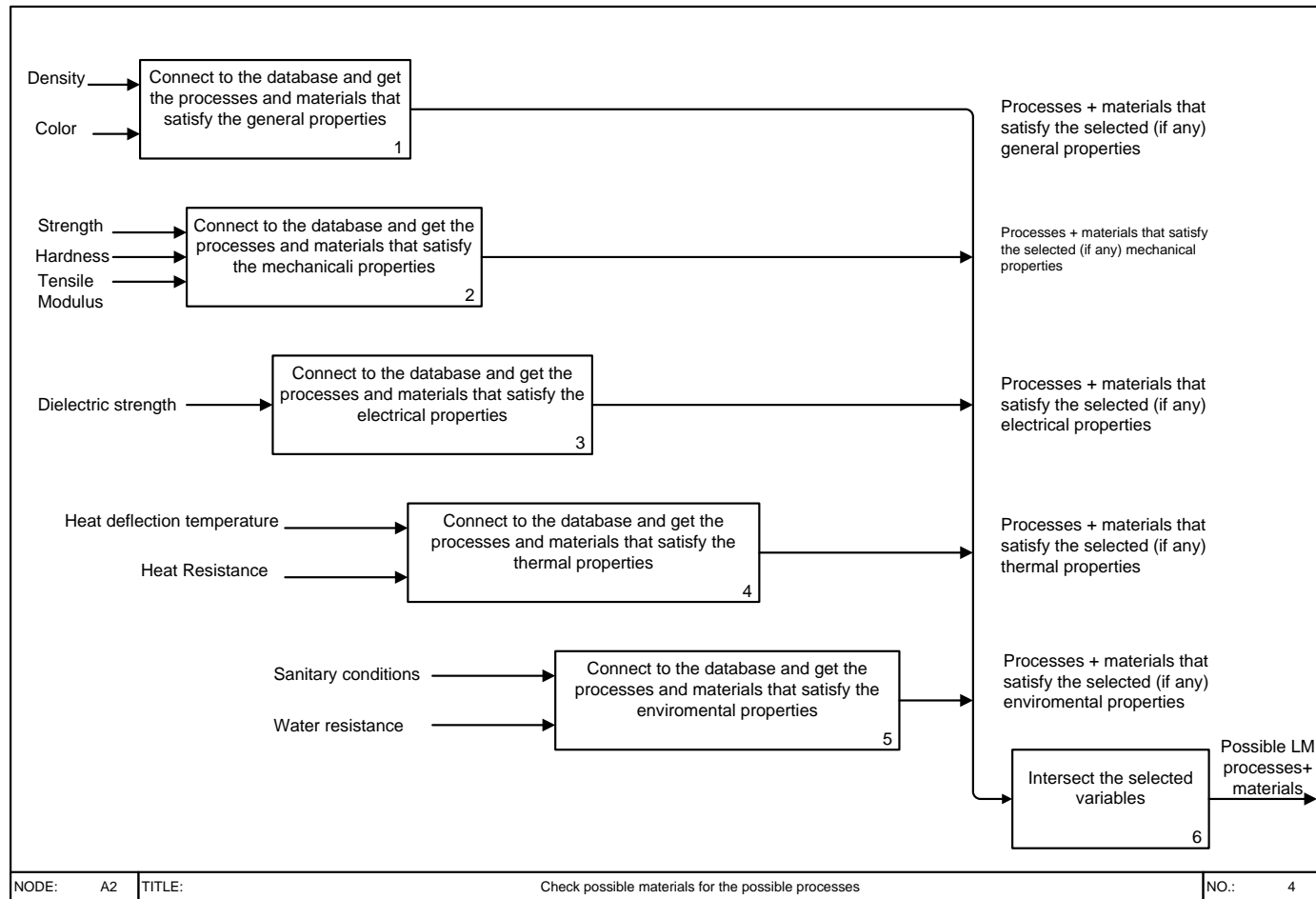


Figure 3.10: A2, Check Possible Materials for the Possible Processes.

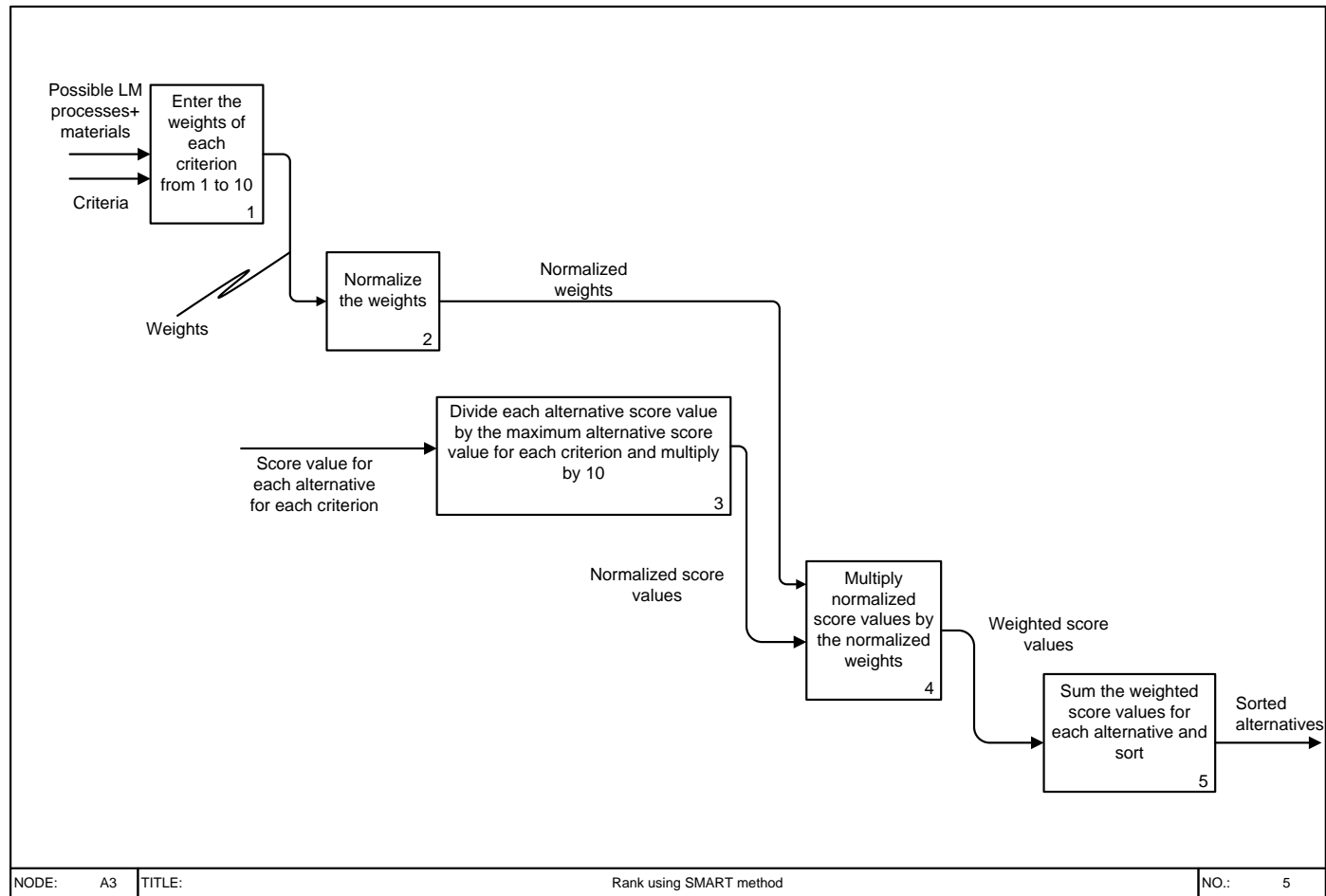
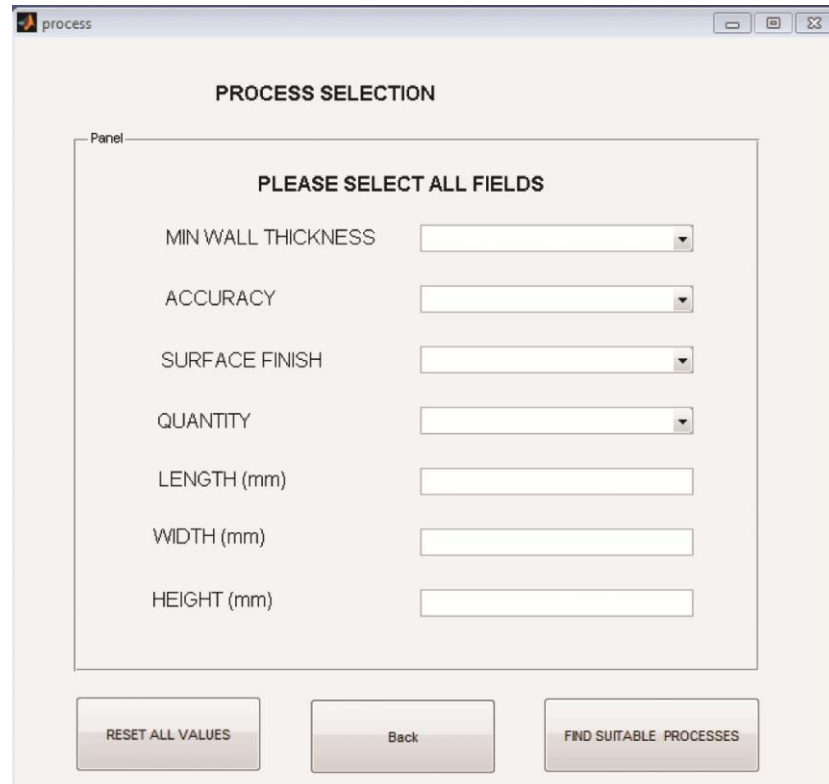


Figure 3.11: A3, Rank Using SMART Method.

The Elements of the Selection Part of the KBS

I. Processes Chain Selection Element

The processes chain selection element is responsible for the selection of the processes that could meet the part requirements regarding minimum wall thickness, accuracy, surface finish, required quantity and dimensions X, Y and Z. Figure 3.12 shows the process selection screen.



The screenshot shows a software window titled "process" with a "PROCESS SELECTION" header. Inside, a panel prompts the user to "PLEASE SELECT ALL FIELDS". The panel includes seven input fields: "MIN WALL THICKNESS", "ACCURACY", "SURFACE FINISH", "QUANTITY", "LENGTH (mm)", "WIDTH (mm)", and "HEIGHT (mm)". The first four are dropdown menus, while the last three are text boxes. Below the panel are three buttons: "RESET ALL VALUES", "Back", and "FIND SUITABLE PROCESSES".

Figure 3.12: Process Selection Screen.

The minimum wall thickness can be selected by selecting an option from three options in a drop down menu: very-thin < 0.5 mm, thin-average $0.5 - 2$ mm and average-wide > 2 mm. The Accuracy can be selected by selecting an option from three options in a drop down menu: tight < 0.1 mm, Average $0.1 - 0.25$ mm and loose > 0.25 mm. The surface finish can be selected by selecting an option from three options in a drop down menu: Excellent $0 - 0.32$ μm , good average $0.32 - 12.5$ μm and average rough > 12.5 μm . The quantity can be selected by selecting an option from four options in a drop down menu: one, low $2- 20$ parts, medium $20-25$ parts and high > 50 parts. The length, width and height are a free text boxes that can be entered manually. The terminologies and range values of minimum wall thickness, accuracy and surface finish chosen in this study are based on

terminologies and ranges values set by Munguia (2009). The output of this element is either the possible processes that could manufacture the part or the reasons why the part cannot be made.

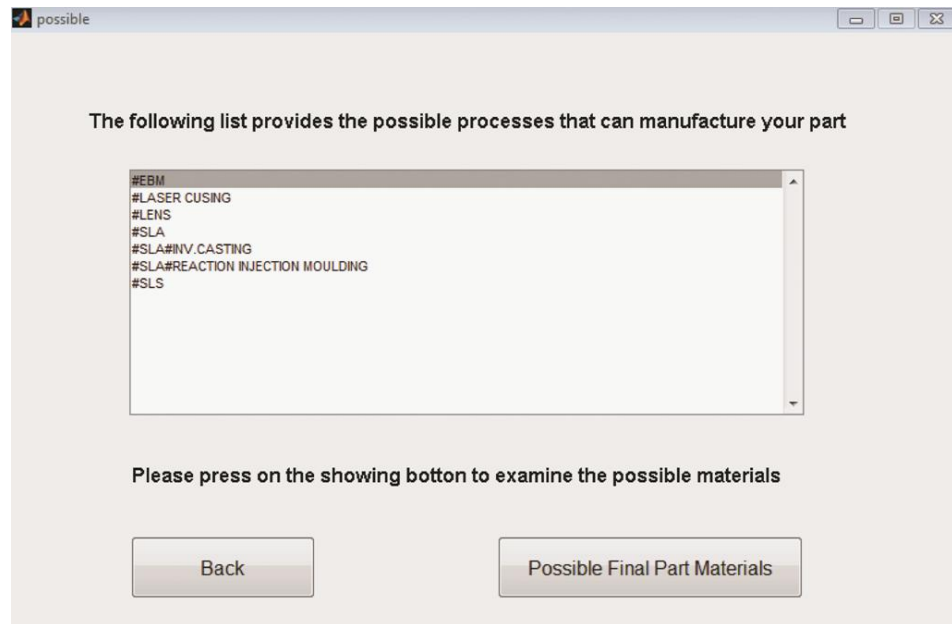


Figure 3.13: List of the Possible Processes that Could Manufacture the Part.

When the user enters the requirements and presses the (Find suitable processes) button another screen appears showing all the possible processes that could manufacture the part as illustrated in Figure 3.13.

Manufacturability Evaluation and Capability Analysis

Manufacturability evaluation is one of the key features of the developed AMDSS. First, the system tells the user if there is a problem with any of the part requirements that could not be met for a specific reason. For example, as shown in Figure 3.14, the available processes in the database cannot meet the required surface finish and the required width (Y) which is the distance along Y axis.

Secondly, in some cases, the part requirements together cannot lead to the selection of a possible AM process. KBS shows a table that clearly identifies the variables which conflict with one another. The benefit is that the user could change some of the part requirements so the part could be made with AM processes.

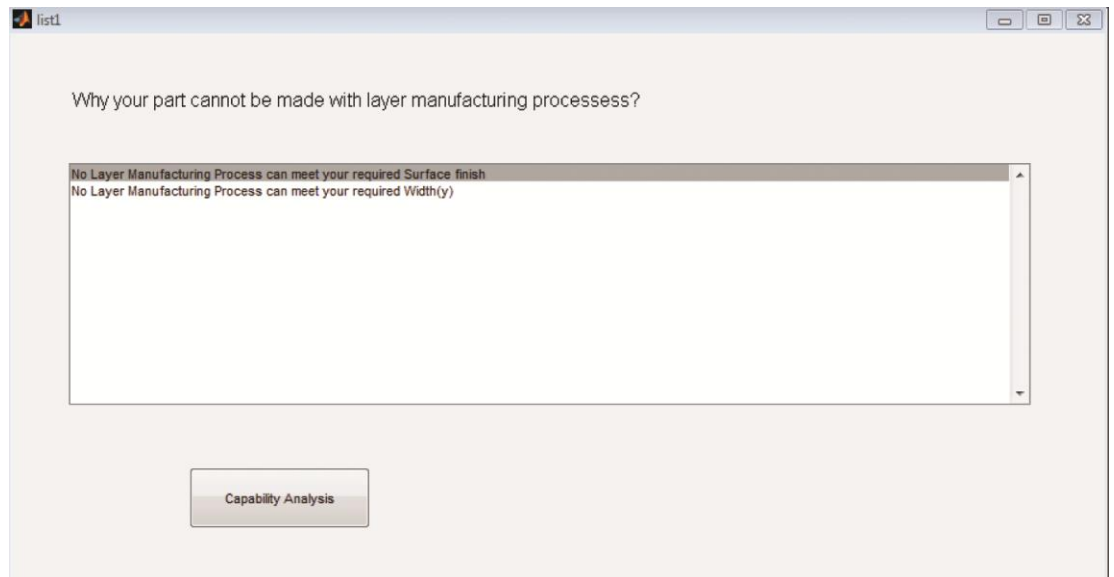


Figure 3.14: Screen Shows the Process Reasons that Prevent AMDSS from Giving a Solution.

If there is no conflict between the two variables the system shows (ok) but if there is a problem the system shows (prb) indicating that there is a problem or a conflict between the two variables. It means that there is no material in the database that could satisfy both variables. For example, Figure 3.15 shows that there is a conflict between X and the wall thickness, X and the accuracy, Y and the wall thickness, Y and the accuracy, Z and the wall thickness, and finally Z and the accuracy.

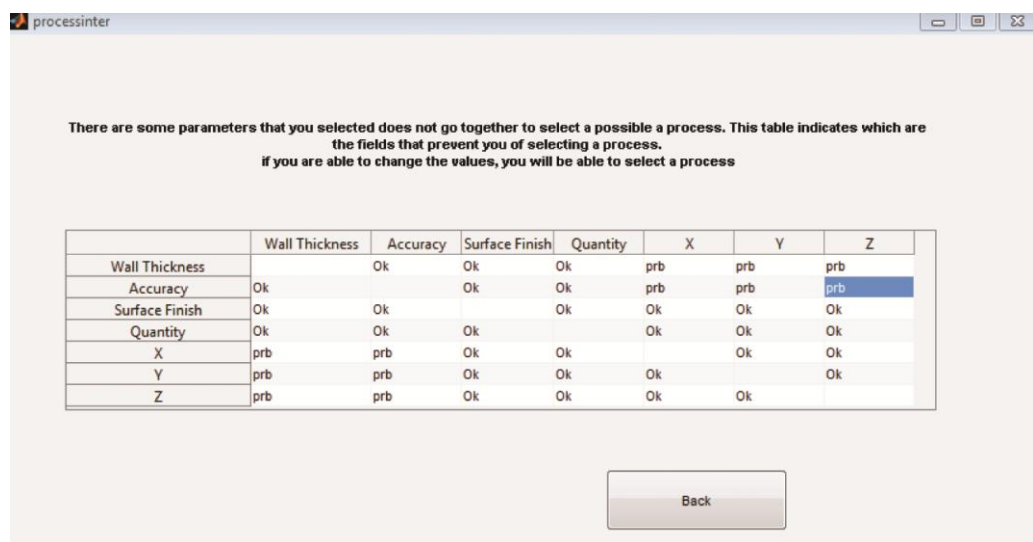


Figure 3.15: Table that Shows the Process Parameters that are not Feasible Together.

Furthermore, KBS shows a warning message which is a specific concern about part quality when the accuracy is very tight and the wall thickness is very thin. The AM technologies do not show satisfactory results in this case.

The KBS gives a warning to the user as shown in Figure 3.16, and lets him select between three options. The first option is to accept the less quality and continue with the system. The second option is to terminate the program. The third option is to compromise between requirements of the part.

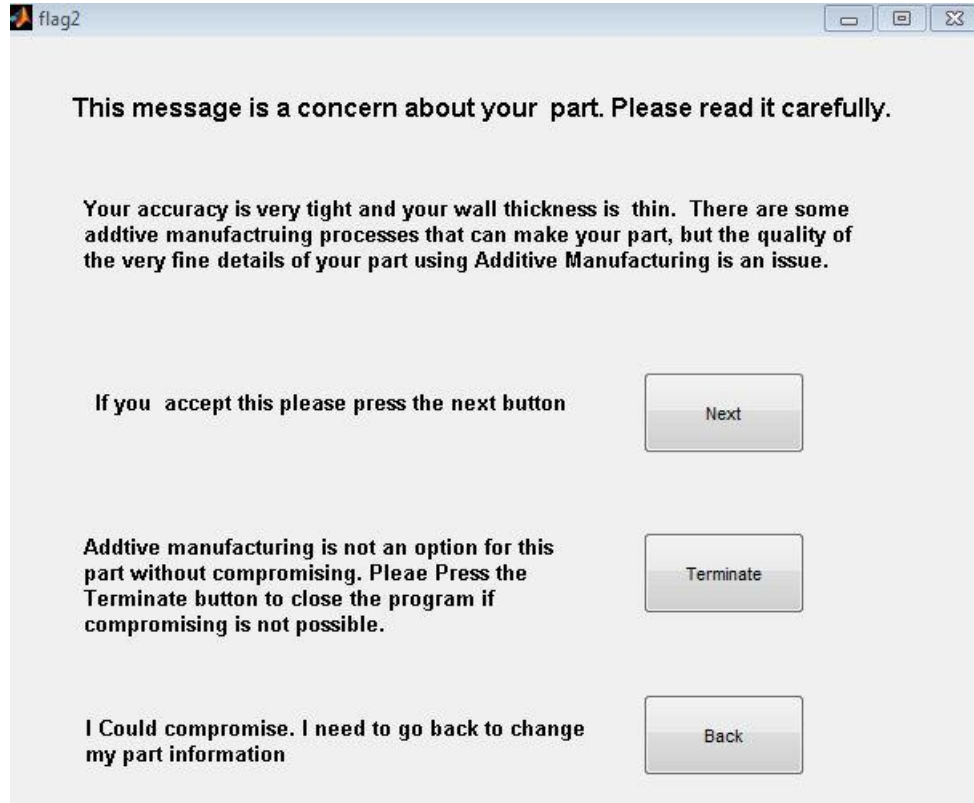


Figure 3.16: A Window that Gives a Concern to the User about Part Quality.

The screenshot shows a window titled 'capability' with a light beige background. The title 'Capability Analysis' is centered at the top. Below the title is a table with three rows and three columns. The first row contains the headers 'Required' and 'Possible'. The second row is 'Length' with values 2000 and 2250. The third row is 'Width' with values 2000 and 1550. The fourth row is 'Height' with values 2000 and 2100.

	Required	Possible
Length	2000	2250
Width	2000	1550
Height	2000	2100

Figure 3.17: Capability Analysis Screen.

The capability analysis is another advantage of the AMDSS. As shown in Figure 3.17, the AMDSS could tell the possible X, Y, and Z and compare them to the required X, Y and Z. For example the required width is 2000 mm while the maximum possible is 1550 mm.

Process selection logic flowchart

Figure 3.18 shows a flowchart that explains how the KBS takes the user inputs and makes the process selection. When the user enters the values of the required fields in the process screen in Figure 3.12, the variables are saved to a workspace. The first step in the process selection is that the KBS connects to the database and creates an empty reasons list in which the KBS adds all the reasons (if any) that prevent the processes in the database from manufacturing the required part. Next, user obtains the values saved by the user in the workspace of process variables: the wall thickness, accuracy, surface finish, quantity, length, width and height.

The KBS gets the lists of the processes that satisfy the required variables. For example, the KBS connects to the database and gets all the processes that are capable of doing the required minimum wall thickness. If the process list is empty this means that no AM process in the database can meet the required wall thickness. The same logic is used for all the process variables. The next step is the intersection between all the process lists. The intersection between the process lists gives a new list which is a list of the processes that satisfy all the requirements.

The logic of the manufacturability evaluation is explained in the following part of the flowchart: if the new list is empty, the reasons list is checked. If the reasons list contains a least one reason, the KBS displays the reasons list but if the reasons list is empty means that there are not common processes that satisfy all the process variables. In this case, an intersection table is displayed. The KBS connects to the database and checks each two process variables together. It tries to retrieve data that satisfies the two variables. If there are common processes that satisfy the two variables together it means that there is no problem between these two variables and if not it means that the user has to modify one of the variables to find a possible process.

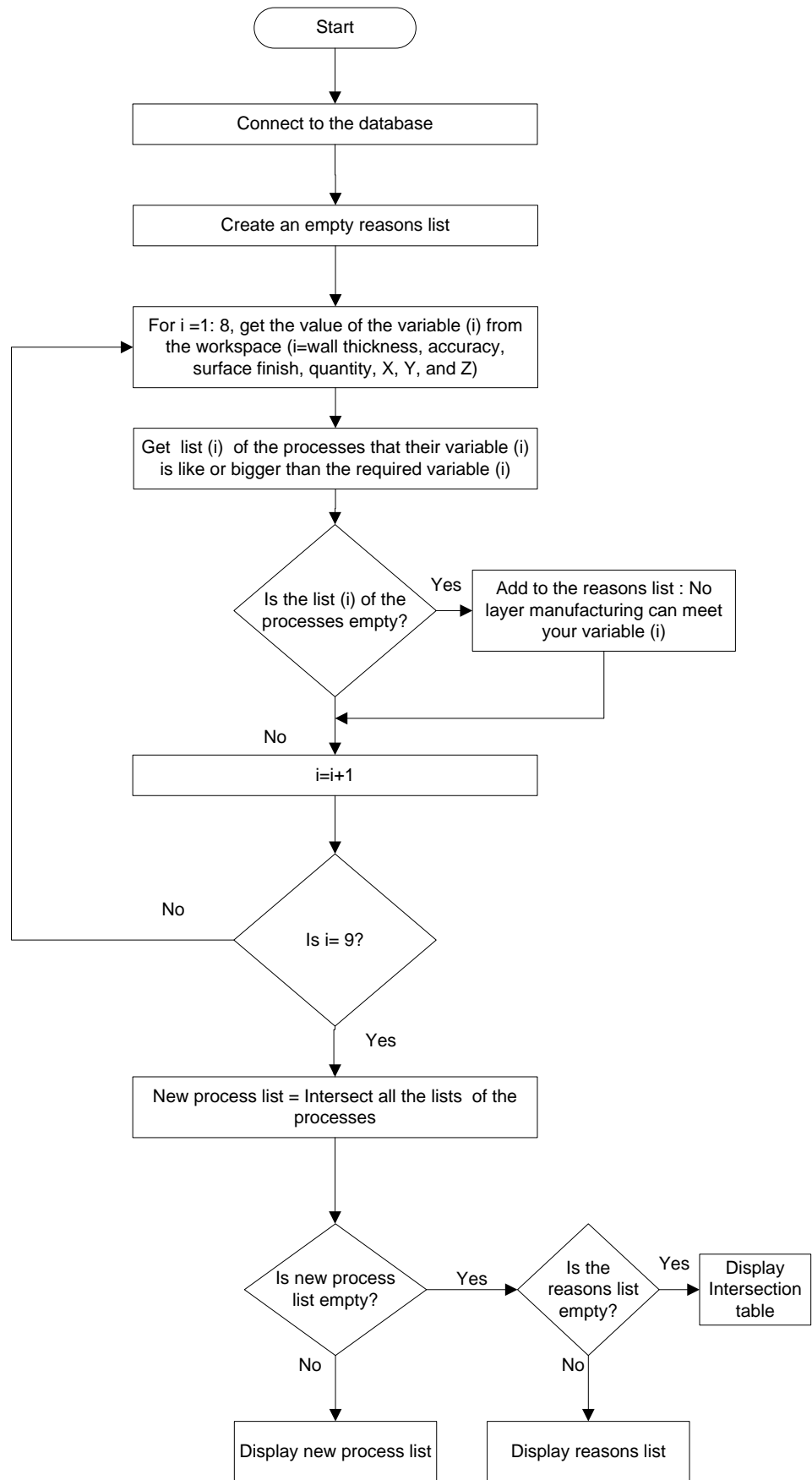


Figure 3.18: Checking AM Processes Flowchart.

II. Material Selection Element

The material selection element is responsible for the selection of the materials of the processes that have passed the processes selection and could meet the part requirements regarding the material properties. The output of this element is either the possible materials that could be potential alternatives for the user or the reasons why the part cannot be made with any of the material available in the database.

All the values of the properties are based on the minimum values. The user has to select at least one property. Figure 3.19 shows the screen where the user enters the values of the material properties and Figure 3.20 shows an example of the list of feasible materials that could manufacture the part.

The screenshot shows a web-based interface for entering material properties. The window title is 'matscreen'. The main heading is 'Material Properties'. Below it, a prompt asks the user to enter values for one or more properties. The form is divided into five sections: General Properties (Density, Color), Thermal Properties (Heat Deflection Temperature, Heat Resistance), Mechanical Properties (Strength, Tensile Modulus, Hardness), Electrical Properties (Dielectric Strength), and Environment (Sanitary Conditions, Water Resistance). At the bottom, there are three buttons: 'Select Possible Materials', 'Reset All Values', and 'Back'.

Figure 3.19: Material Properties Screen.

	MATERIAL ...	PROCESS	MATERIAL	STRENGTH	MODULUS	HARDNESS	DENSITY	DIELECTRIC STRENGTH	HDT
1	2 #SLA		NANO TOOL	78	11400	94	2	3	225
2	4 #SLA		PROTO THERM 12120	77	3250	87	1	3	146
3	5 #SLA		PROTP THERM 12110	66	2950	86	1	3	53
4	6 #SLA		PROTOGEN 18920	70	2623	88	1	3	96
5	7 #SLA		PROTOGEN 18120	69	2900	88	1	3	97
6	12 #SLA		PROTOGEN 18420	68	2960	87	1	3	98
7	20 #SLA		SOMOS 7110 EPOXY PHOTOPOLYMER	69	2413	85	1	3	89
8	37 #SLA		ACCURA BLUESTONE	68	11700	92	2	3	284
9	38 #SLA		ACCURA ACCUGEN	67	3030	82	1.1000	0.1000	0
10	39 #SLA		ACCURA 60	66	3100	86	1.2100	0.1000	55
11	40 #SLA		ACCURA 45HC	61	2960	87	1.2000	0.1000	103
12	43 #SLA		ACCURA 48HTR	67	3680	86	1	3	130
13	45 #SLA		ACCURA 55	68	3380	85	1	3	58
14	68 #SLA		ACCURA 40	61	3321	84	1	3	114
15	139 #SLA#DIV.CASTING		A 201 (A12010)	427	74600	0	0.0028	0	0
16	140 #SLA#DIV.CASTING		354 (A03540)	345	76700	0	0.0028	0	0
17	141 #SLA#DIV.CASTING		C90710	390	82000	0	0.0088	0	0
18	142 #SLA#DIV.CASTING		C86500	838	103000	0	0.0079	0	0
19	143 #SLA#DIV.CASTING		G10500	705	216000	0	0.0079	0	0
20	144 #SLA#DIV.CASTING		ASTM CF-20	580	199000	0	0.0078	0	0
21	157 #SLA		ACCURA 10	76	3532	86	1.2100	0.1000	58

Figure 3.20: List of Possible Processes and Material that Could Manufacture the Part.

Material Properties Evaluation and Capability Analysis

Material properties evaluation is one of the key features of the developed AMDSS. First, the system tells the user if there is a problem with any of the material requirements that could not be met for a specific reason. For example, as shown in Figure 3.21 the available materials in the database cannot meet the required strength. Secondly, in some cases, the material requirements together cannot lead to the selection of a possible AM material. The KBS shows a table that clearly identifies the variables conflicting with each other. The benefit is that the user could change some of the material requirements so the part could be made with AM processes.

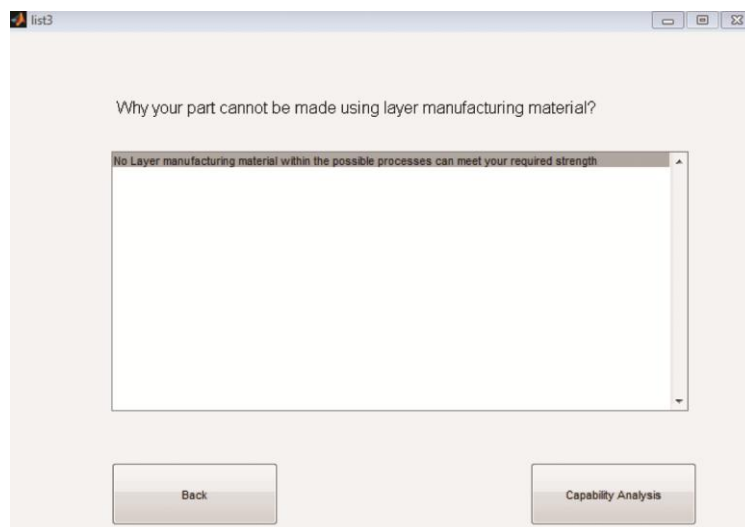


Figure 3.21: Screen Shows the Material Reasons that Prevent AMDSS from Giving a Solution.

For example, Figure 3.22 shows that there is a conflict between colour and strength. The user could change one of them to finally have a possible AM solution.

	Strength	Tensile	Hardness	HDT	Color	Density	Dielectric strength	Sanitary	Water resist	Heat resist
Strength		Not selected	Not selected	Not selected	prb	Not selected	Not selected	Not selected	Not selected	Not selected
Tensile	Not selected		Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected
Hardness	Not selected	Not selected		Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected
HDT	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected	Not selected	Not selected	Not selected
Color	prb	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected	Not selected	Not selected
Density	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected	Not selected
Dielectric strength	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected
Sanitary	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected
Water resist	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected
Heat resist	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	

Figure 3.22: Table that shows the material Parameters that are not Feasible Together.

Besides the material properties evaluation, the capability analysis is another advantage of the AMDSS. As shown in Figure 3.23 the AMDSS could tell the possible material capabilities in the database regarding density, strength, hardness, dielectric strength, heat deflection temperature and tensile modulus and compare them to the required material requirements. For example, the required strength is 1500 MPa while the maximum available in the database is 1430 MPa.

In addition to that, there is a button called (possible processes colour) which when pressed allows the user to browse the available colours of the different AM processes.

	Part requirements	Material capabilities
Density		8.1900
Strength	1500	1430
Hardness		300
Dielectric Strength		18.5000
Heat Deflection Temperature		284
Tensile Modulus		216000

Figure 3.23: Material Capability Analysis.

Material Selection Logic Flowchart

Figure 3.24 shows a flowchart that explains in detail how the material selection was done. When the user enters the values of one or more variables in the material properties screen shown in Figure 3.19 the variables are saved to a workspace. The material properties used are: density, colour, tensile strength, modulus, heat deflection temperature (HDT), heat resistance, sanitary conditions (medical consideration) and water resistance. These material properties were selected because they are common properties used by design engineers and users when they need to make selections. In addition, there is limited data availability for other AM material properties.

The first step in the flowchart is that the KBS connects to the database and creates an empty reasons list in which the KBS adds all the reasons that prevent AM materials available in the database (within the feasible processes) from manufacturing the required part. Next, the KBS retrieves the material variables (material properties) entered by the user. The variables are divided into two groups. The first group is the (minimum values group). For this group, the KBS obtains from the database a material list that has values bigger than or equal the required values set by users. This group includes six variables which are: density, strength, tensile modulus, hardness, dielectric strength and heat deflection temperature. The second group is the (like values group). For this group, the KBS obtains from the database a material list that has values like exactly the values set by users. This group includes four variables which are: colour, heat resistance, sanitary conditions and water resistance.

Each time the KBS obtains a material list for each material variable, a checking is done if the material list is empty which means that no AM materials in the database within the possible processes can meet the required values set by users for this specific material variable. The KBS adds to the reasons list this reason. The next step is to check which material variables are selected by users because they do not have to select all variables. An intersection between the selected material lists is done. The intersection between the selected material lists gives a new list which is a list of the materials that satisfy all the requirements.

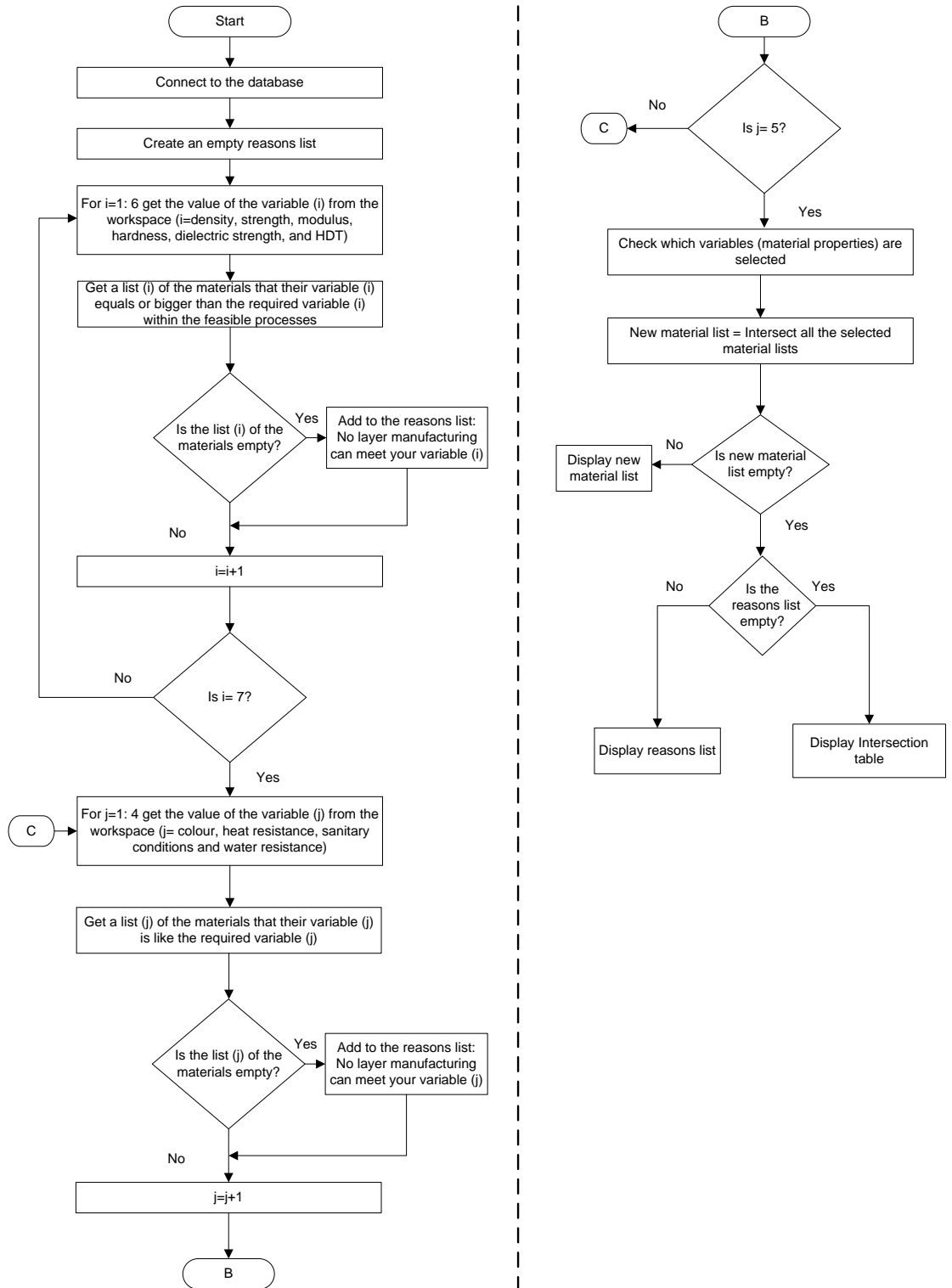


Figure 3.24: Checking AM Materials Flowchart.

The logic of the material properties evaluation and capability analysis is explained in the following part of the flowchart: if the new list is empty, the reasons list is checked. If the reasons list contains a least one reason, the AMDSS displays the reasons list but if the reasons list is empty means that there is no common material that satisfies all the materials variables. In this case, an intersection table is displayed. The KBS connects to the database and checks each two material variables together. It tries to retrieve data that satisfy the two variables. If there is at least a single common process that satisfies the two variables together it means that there is no problem between these two variables and if not it means that the user has to modify one of these two variables to find a possible material.

III. Ranking Element

The third element in the KBS selection part is ranking. Any ranking process requires criteria or attributes to rank alternatives according to them. The selection of the ranking criteria to be used in the developed system was made after exploring literature surveys, checking available material properties data and asking AM industry experts. In the literature, Hermann and Allen (1999) have used two types of criteria: 1- process criteria such as: cost, minimum wall thickness, accuracy and build time and 2- material criteria such as: availability, density, elastic modulus, tensile strength, elongation and heat deflection temperature. Byun and Lee (2005) have used accuracy, surface finish, strength, elongation, part cost and build time criteria. Hanumaiah et al. (2006) have used cost, lead time, accuracy, surface finish, strength, and flexibility to changes (selection was focused on rapid tooling) criteria. Munguia et al. (2010) have used geometry, appearance, mechanical requirements and functional requirements criteria.

The criteria selected for the AMDSS as shown in Figure 3.25 were: strength, hardness, heat deflection temperature, density, dielectric strength, modulus, wall thickness, accuracy and surface finish. The user enters values for the criteria. The values entered are from one to ten. The user does not have to enter them all. If the fields are left empty the system considers all the weights to be equal. Values could be repeated, meaning that users could use any weight value several times.

When the user presses the next button, a final ranking screen appears as shown in Figure 3.26. It includes three buttons which are: (Possible Intermediate Materials), (Finishing Options), and (Machine selection).

Please rank the following criteria according to their importance. If you are not interested in any of the criteria leave the cell empty.

Use a Scale from 1 (Not Important) to 10 (Very Important)

Criteria

1- STRENGTH	<input type="text"/>
2- HARDNESS	<input type="text"/>
3- HDT	<input type="text"/>
4- DENSITY	<input type="text"/>
5- DIELECTRIC STRENGTH	<input type="text"/>
6-MODULUS	<input type="text"/>
7- WALL THICKNESS	<input type="text"/>
8- ACCURACY	<input type="text"/>
9-SURFACE FINISH	<input type="text"/>

Back Next

Figure 3.25: Criteria Screen.

FINAL RANKING

Please select the process/material that you want

	Process	Material	Score
1	#SLA	NANO TOOL	71
2	#SLA	PROTO THERM 12120	62
3	#SLA	PROTOGEN 18920	60
4	#SLA	ACCURA 10	49
5	#SLA#INV.CASTING	G10500	48
6	#SLA#INV.CASTING	ASTM CF-20	46
7	#SLA#INV.CASTING	C86500	45
8	#SLA#INV.CASTING	A 201 (A12010)	39
9	#SLA#INV.CASTING	C90710	38
10	#SLA#INV.CASTING	354 (A03540)	38

Possible Intermediate Materials

Finishing Options

Machine selection

Please push the technical summary button after you have selected the process/material from the table on the left, intermediate material (if applicable), finishing methods and machine.

Technical Summary

Back

Figure 3.26: Final Ranking Screen.

Ranking Logic flowchart

Ranking is done using a method called SMART method. Figure 3.27 and Figure 3.28 show flowcharts that explain how the SMART method was used. The first step is to get from the workspace all the processes and materials that satisfy the user requirements. These are the successful candidates that passed all the required inputs for processes and materials. The next step is to get the normalized score value of each alternative regarding each criteria. In SMART method in general, user can assign a value usually between 1 and 10 or 1 and 100 that represents the performance of each alternative regarding certain criteria. Usually it is a qualitative value set by the user. This value is called in the developed system normalized score value and it has a range between 1 and 10. In the developed system, there are nine criteria. Six of these criteria are quantitative: strength, hardness, heat deflection temperature, density, dielectric strength, and modulus; three are qualitative wall thickness, accuracy and surface finish. For the quantitative criteria, the normalized value is calculated as follows: for each criterion, the KBS gets the maximum value of this criterion of the successful candidates list and the normalized score is calculated by dividing the value of each alternative by the maximum value and finally multiplied by ten. For example the strength criterion: the strength of each alternative is divided by the maximum strength in the successful candidates list and then multiplied by ten. The same approach was taken for all the quantitative criteria.

For the qualitative criteria, each of them has three levels that user can choose between these levels like for example the wall thickness: the user can select 1- Average-Wide, 2- Thin-Average, and 3- Very-Thin. The normalized score values for each process regarding the minimum wall thickness criteria for average-wide is four, for thin-average is seven and finally for very-thin is ten. The same approach was taken for the other qualitative criteria: accuracy and surface finish. Next the KBS gets all the weights of the user for each criterion. If a weight is not set by a user the system gives it a value of one. Next a variable called weighted score value is calculated: $\text{Weighted score value} = \text{normalized score value of each alternative} \times \text{weight of the user for each criterion}$. The sum of all the weighted score values for each alternative gives the final score. Next the alternatives are ranked according to the final score in descending order.

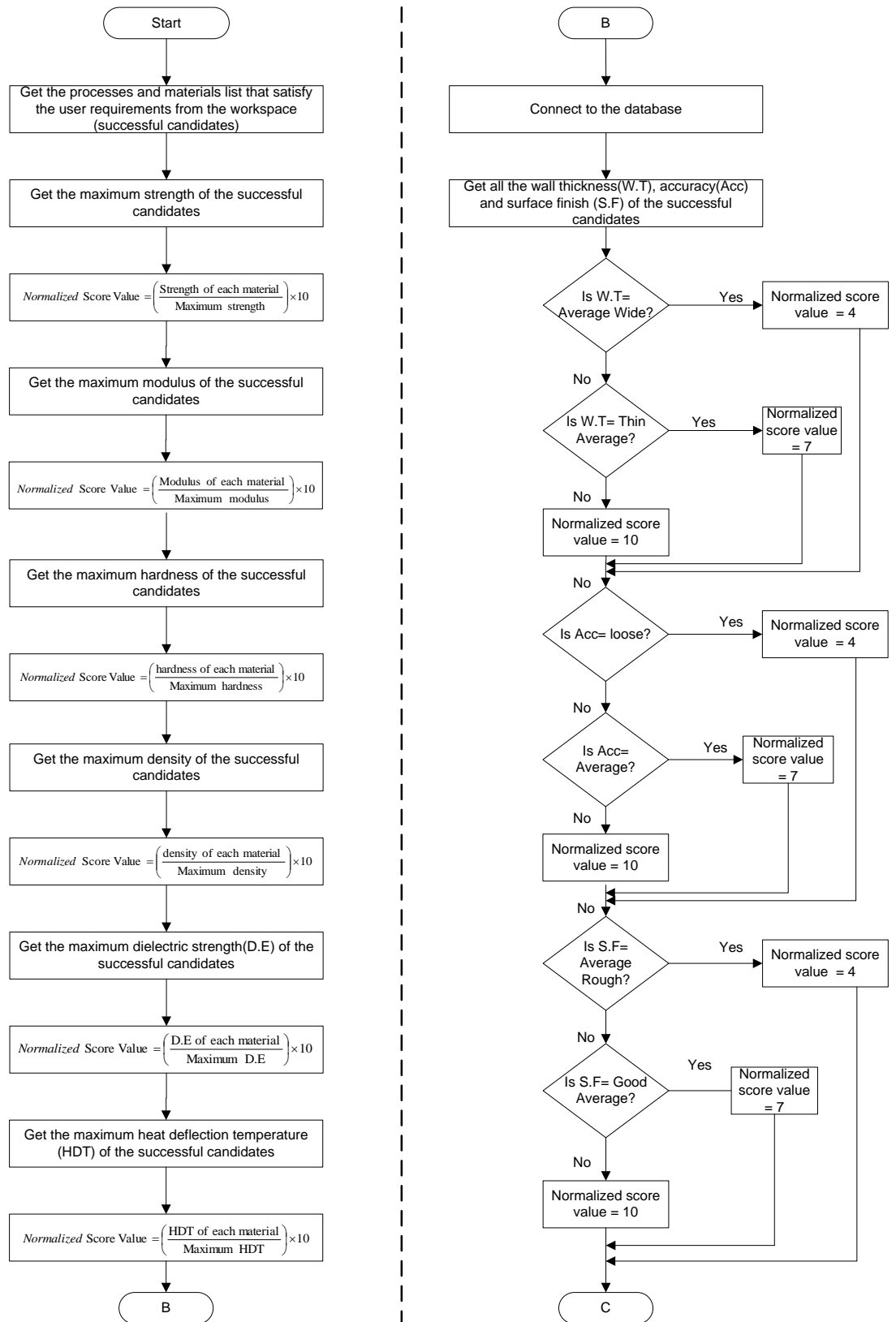


Figure 3.27: SMART Ranking Flowchart

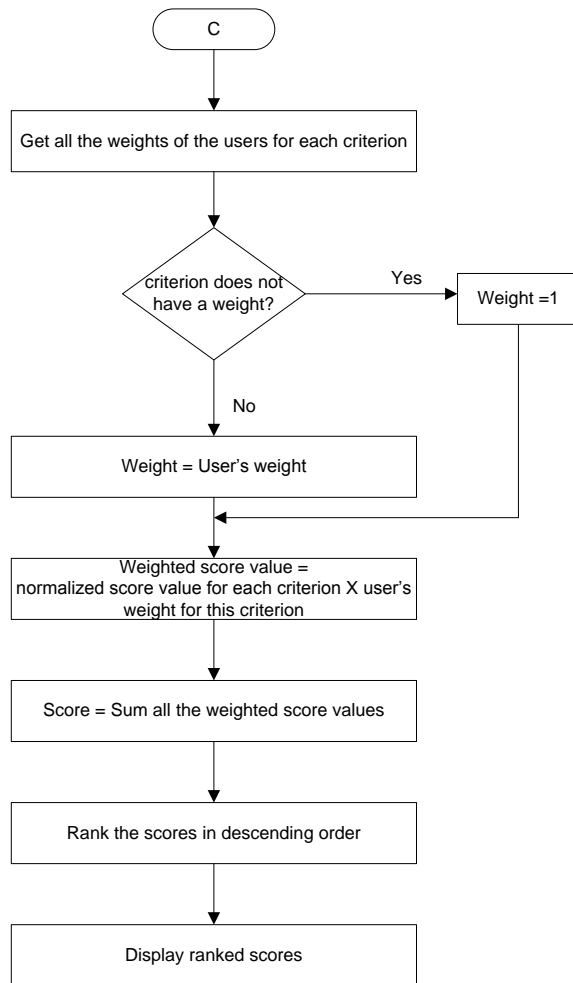


Figure 3.28: SMART Ranking Flowchart (continued).

IV. Intermediate Material Selection Element

When the (Possible Intermediate Material) button in Figure 3.26 is pressed, a screen appears to ask the user about the AM process chain that he needs to select its intermediate material as shown in Figure 3.29. This list shows only the process chain and does not show any single process by itself because single processes do not need intermediate materials. When the user selects the process (SLA + Investment Casting in this case), the KBS connects to the database, retrieves from the intermediate material table all the intermediate materials of the process selected and shows them in a table as shown in Figure 3.30. The intermediate material in this case is the material of the SLA process, while the final material is the material for investment casting.

The user can select more than one intermediate material at the same time using the control button. This could be the case when there are more than two processes in the process chain. When the selection has been made the back button returns to the final ranking screen. The selections of the user are saved for retrieval purpose.

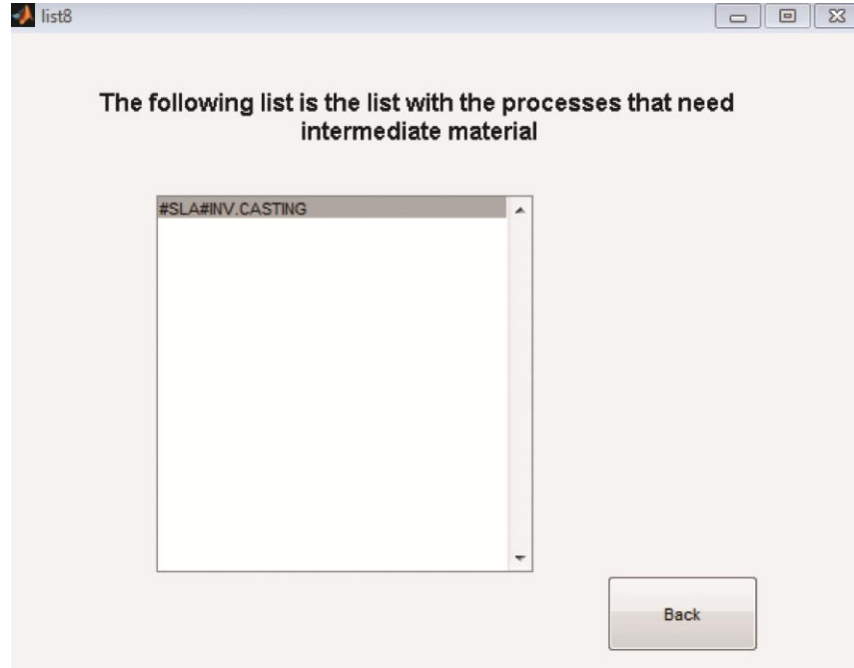


Figure 3.29: List of the Processes that Need Intermediate Materials.

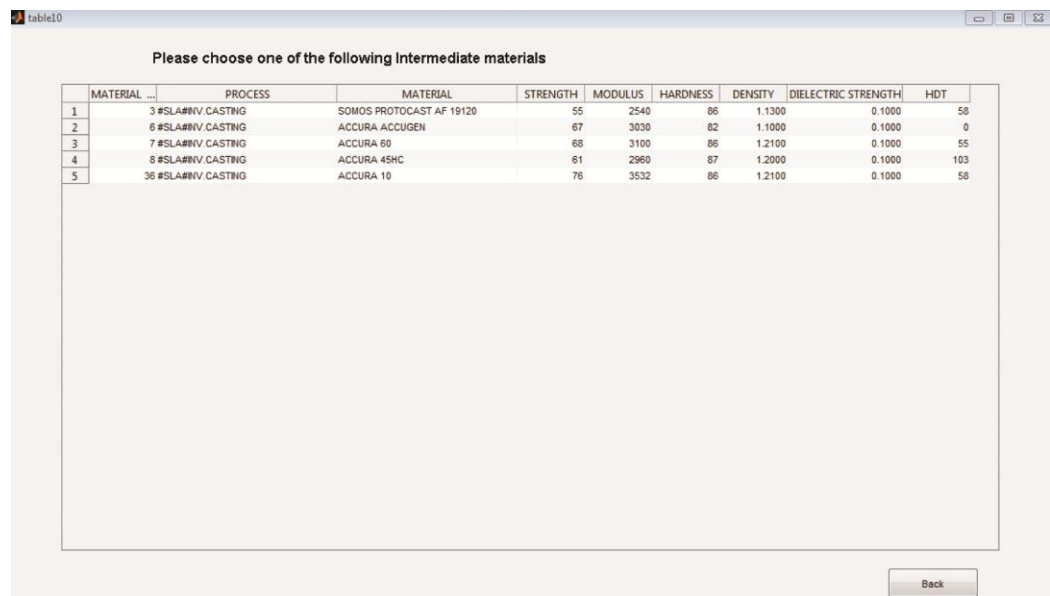


Figure 3.30: Selection of Intermediate Material Screen.

V. Finishing Options Selection Element

When the (Finishing Options) button shown in Figure 3.26 is pressed, a screen appears to ask the user to select an appropriate finishing option as shown in Figure 3.31. By double clicking on the process that he needs to select its finishing option (SLA in this case), the KBS connects to the database, retrieves from the finishing options table all finishing options of the process selected and shows them in a list as shown in the finishing options screen shown in Figure 3.32.

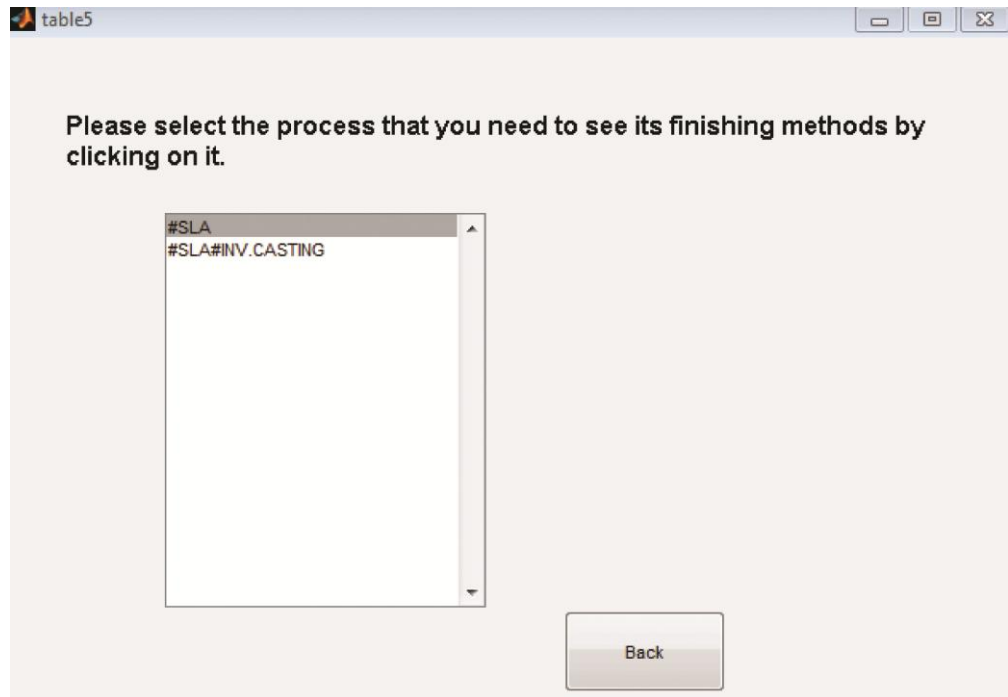


Figure 3.31: Selection of the Process that the User Wants to See its Finishing Methods.

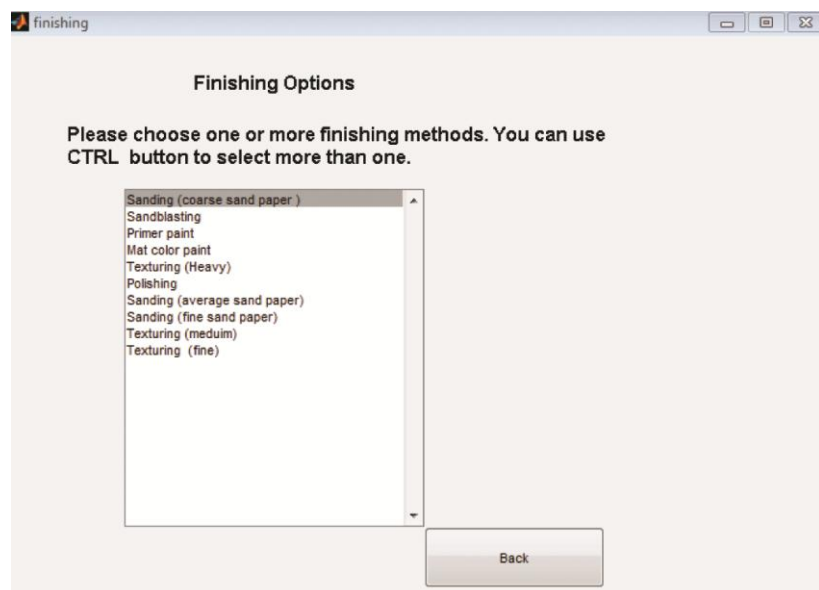


Figure 3.32: Selecting from the Finishing Options Screen.

The user can select more than one finishing option by pressing the CTRL button. When the selection has been made done the back button returns to the final ranking screen. The selections of the user are saved for retrieval purpose.

VI. Machines Selection Element

When the (Machine Selection) button shown in Figure 3.26 is pressed, a screen appears to ask the user to select a specific machine as shown in Figure 3.33. By double clicking on the process needed, the KBS connects to the database, retrieves from the machines table all machines of the process selected and shows them in a table as shown in Figure 3.34. The user can press in any cell in the row of the machine needed. When the selection has been made the back button returns to the final ranking screen. The selections of the user are saved for retrieval purpose.

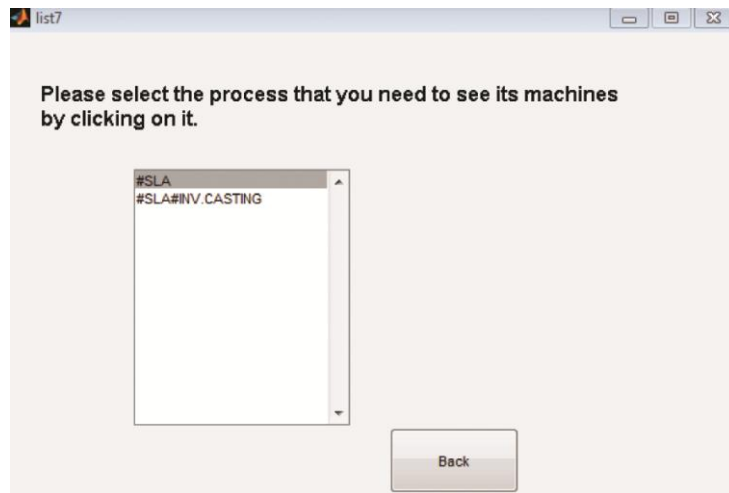


Figure 3.33: Selection of the Processes that the User Needs to See its Machines Screen.

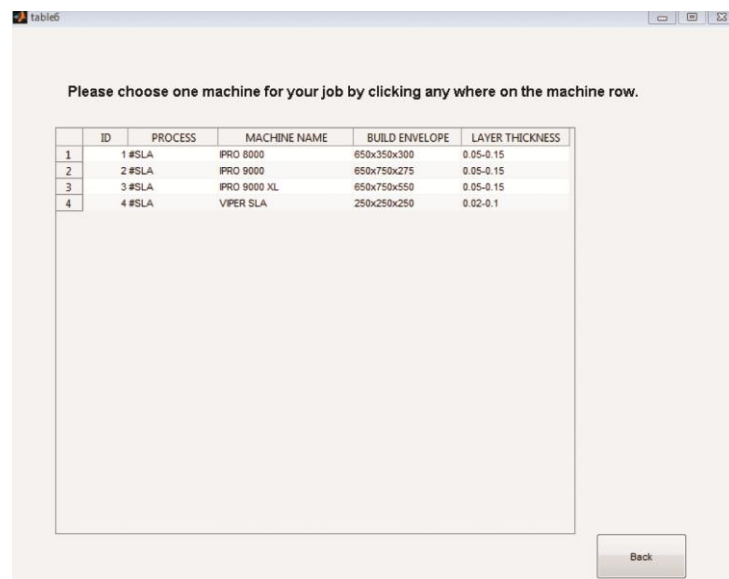


Figure 3.34: Selection of the Machines Screen.

Technical Summary

After making all the selections of the intermediate materials, finishing options, and machine selection there is a button in the final ranking screen (Figure 3.26) called (Technical Summary). This button when pressed shows a screen that contains a summary of all the selections that have been made. The KBS retrieves all the saved user’s selections and displays them in one table.

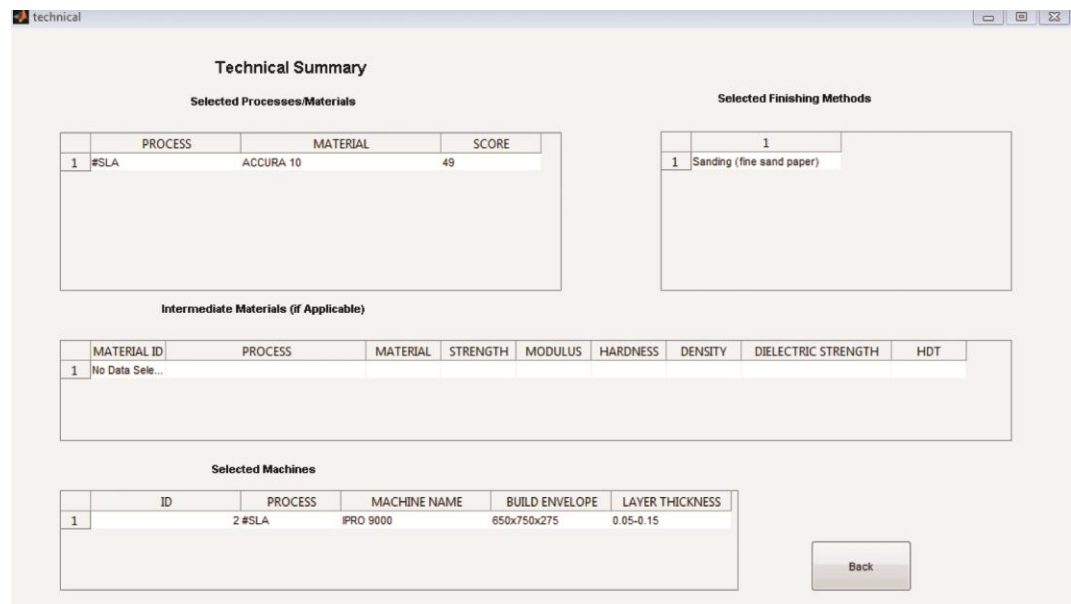


Figure 3.35: Technical Summary Screen.

For illustration purpose, Figure 3.35 shows a technical summary. The process selected is SLA, the material is ACCURA 10. The finishing method for the SLA process is sanding (fine sand paper). There is no intermediate machine selected because this is a single process and not a chain. The selected SLA machine is IPRO 9000. Choosing finishing options, the intermediate material or the machines is not mandatory. The user can select the process and the final material only. The information presented in the technical summary screen is according to user selection.

2. Browse Part

If the user needs a specific material and needs to explore the different available processes that could manufacture a part using this specific type of material, he presses the specific material module button and is presented a list of the current materials in the database. The KBS connects to the database and retrieves all the current materials available in the material table and shows them in a pop-up menu

shown in Figure 3.36. The pop-up menu will be always displaying the current materials in the database, if a material is deleted it will disappear from the pop-up menu and if a material is added it will appear in the pop-up menu. When a user selects a material, he presses search the database and the KBS connects to the database and shows a table that presents all the processes that could use this type of material.

If the user knows the process and needs to explore the different available materials for this process, he presses the specific process module button and is presented with the current list of the processes in the database. The KBS connects to the database and retrieves all the current processes available in the process table and shows them in a pop-up menu shown in Figure 3.37. The pop-up menu will be always displaying the current processes in the database, if a process is deleted it will disappear from the pop-up menu if a process is added it will appear in the pop-up menu. When a user selects a process, he presses search the database and the KBS connects to the database and shows a table that presents all the materials that could be used by the selected process.

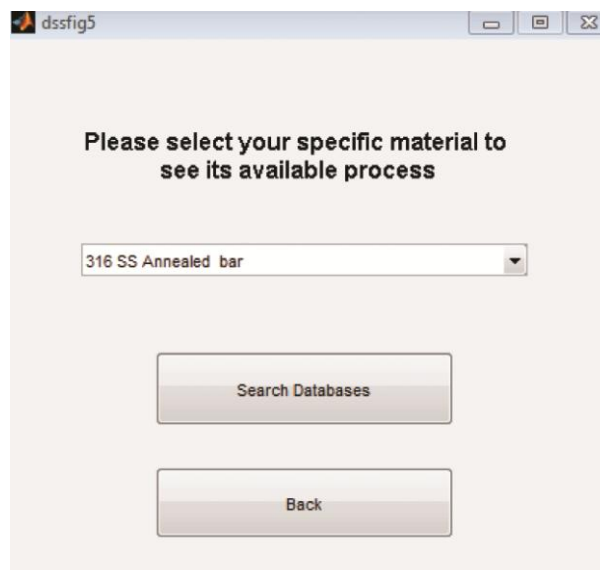


Figure 3.36: Browsing Processes by Material.

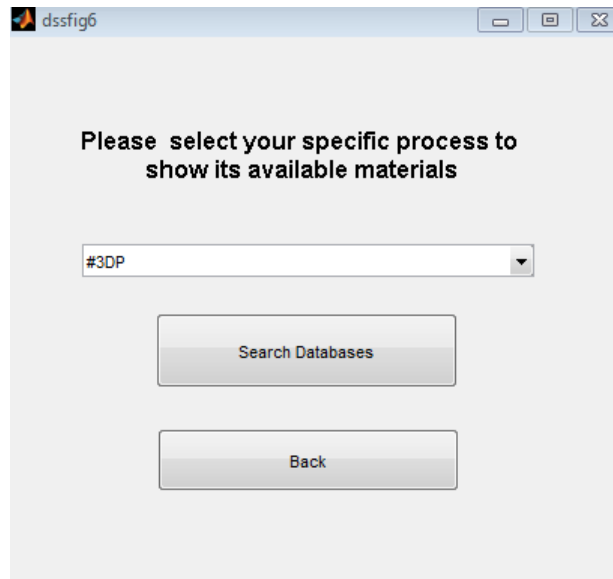


Figure 3.37: Browsing Materials by Process.

3. Update Part

The update panel contains five buttons called add a process, add a material, add an intermediate material, add a machine, and add a finishing process. To add a process to the database user presses the (ADD A PROCESS) button and a window appears as shown in Figure 3.38. The user has to enter all the fields so it can be added in the database. The requested fields are: process name, minimum wall thickness, accuracy, surface finish, quantity and dimensions (X, Y, and Z) of the maximum build envelope of the process. When adding a new process, the process name must be preceded by “#” as shown in Figure 3.37 and if it is a process chain that has more than one stage it must have “#” between each stage. When the user presses the (ADD) button the KBS connects to the database and inserts the new process in it.

The image shows a software window titled "update1" with a light beige background. At the top center, the text "ADD A NEW PROCESS" is displayed in bold. Below this, there are eight input fields arranged vertically. The first field is labeled "Process" and is a standard text box. The next three fields are labeled "Min Wall Thickness", "Accuracy", and "Surface Finish", each with a dropdown arrow on the right side. The fifth field is labeled "Quantity" and also has a dropdown arrow. The final three fields are labeled "Max X", "Max Y", and "Max Z", which are standard text boxes. At the bottom of the window, there are two buttons: "ADD" on the left and "Back" on the right, both with a slight gradient and rounded corners.

Figure 3.38: Adding a New Process.

To add a material to the database user presses the (ADD A MATERIAL) button and a window appears as shown in Figure 3.39. The user has to add all the fields. The fields are: process name, material strength, modulus, hardness, heat deflection Temperature, dielectric strength, colour, water resistance, sanitary conditions, density and heat resistance. The user could select between two options YES or NO in pop-up menus for water resistance, sanitary conditions and heat resistance variables. When the user presses the (ADD) button the KBS connects to the database and inserts the new material in it.

To add an intermediate material to the database user presses the (ADD INTERMEDIATE MATERIAL) button and a window appears as shown in Figure 3.40. The user has to enter all fields and they are the same as the material fields. When the user presses the (ADD) button the KBS connects to the database and inserts the new intermediate material in it.

The screenshot shows a web application window titled 'update2' with the heading 'ADD A NEW MATERIAL'. The form contains the following fields:

Process	<input type="text"/>	Color	<input type="text"/>
Material	<input type="text"/>	Water Resistance	<input type="text"/>
Strength (MPa)	<input type="text"/>	Bio-compatible	<input type="text"/>
Tensile Modulus (MPa)	<input type="text"/>	Density (g/cm3)	<input type="text"/>
Hardness (Shore D)	<input type="text"/>	Heat Resistance	<input type="text"/>
Heat Deflection Temperature (°C)	<input type="text"/>	Hardness (Vickers)	<input type="text"/>
Dielectric Strength (KV/mm)	<input type="text"/>	Melting Point (°C)	<input type="text"/>

At the bottom of the form are two buttons: 'ADD' and 'Back'.

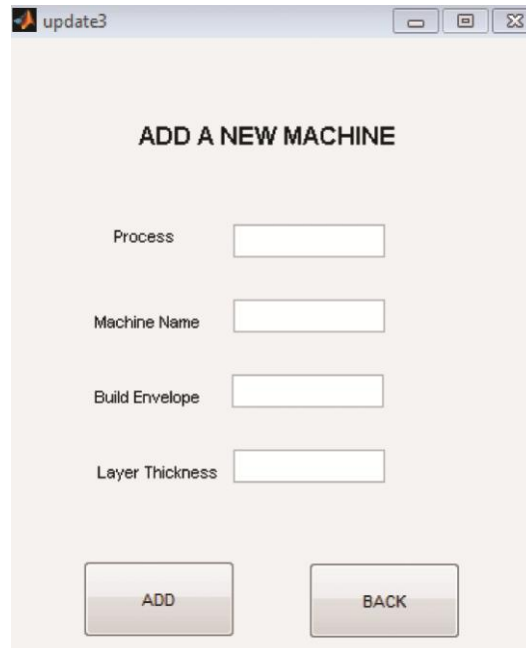
Figure 3.39: Adding a New Material.

The screenshot shows a web application window titled 'update5' with the heading 'ADD A NEW INTERMEDIATE MATERIAL'. The form contains the following fields:

Process	<input type="text"/>	Color	<input type="text"/>
Material	<input type="text"/>	Water Resistance	<input type="text"/>
Strength (MPa)	<input type="text"/>	Sanitary Conditions	<input type="text"/>
Tensile Modulus (MPa)	<input type="text"/>	Density (g/cm3)	<input type="text"/>
Hardness (Shore D)	<input type="text"/>	Heat Resistance	<input type="text"/>
Heat Deflection Temperature (°C)	<input type="text"/>	Hardness (Vickers)	<input type="text"/>
Dielectric Strength (KV/mm)	<input type="text"/>	Melting Point (°C)	<input type="text"/>

At the bottom of the form are two buttons: 'ADD' and 'Back'.

Figure 3.40: Adding a New Intermediate Material.

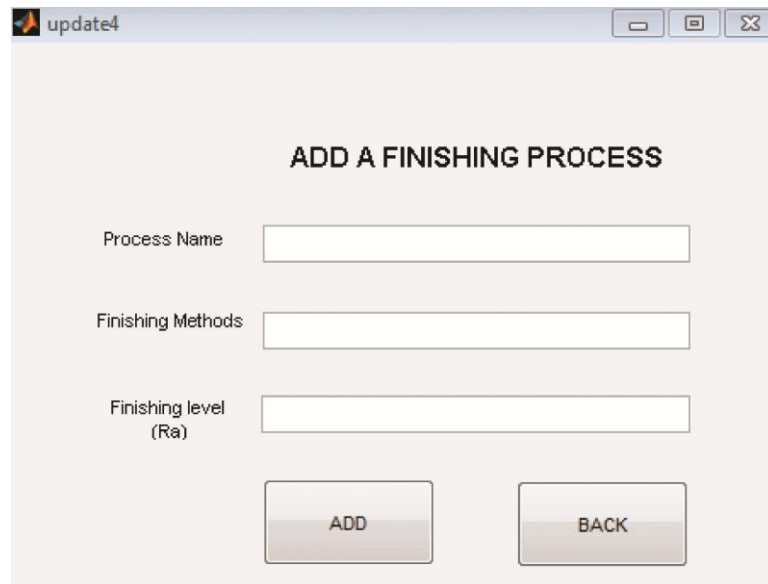


The image shows a web browser window with the title 'update3'. The main heading is 'ADD A NEW MACHINE'. Below the heading, there are four text input fields, each with a label to its left: 'Process', 'Machine Name', 'Build Envelope', and 'Layer Thickness'. At the bottom of the form, there are two buttons: 'ADD' on the left and 'BACK' on the right. The background of the form is a light beige color.

Figure 3.41: Adding a New Machine.

To add a machine to the database user presses the (ADD A MACHINE) button and a window appears as shown in Figure 3.41. All the fields have to be filled. The fields are: process name, machine name, build envelope and layer thickness. When the user presses the (ADD) button the KBS connects to the database and inserts the new machine in it.

To add a finishing process to the database user presses the (ADD A FINISHING PROCESS) button and a window appears as shown in Figure 3.42. All the fields have to be filled. The fields are: process name (AM process) and possible finishing methods. When the user presses the (ADD) button the KBS connects to the database and inserts the new finishing process in it.



The screenshot shows a web browser window with the title 'update4'. The main content area has a light beige background and is titled 'ADD A FINISHING PROCESS' in bold black text. Below the title, there are three input fields stacked vertically. The first is labeled 'Process Name', the second 'Finishing Methods', and the third 'Finishing level (Ra)'. Each label is to the left of its corresponding white input box. At the bottom of the form, there are two rectangular buttons with a gradient background. The left button is labeled 'ADD' and the right button is labeled 'BACK'.

Figure 3.42: Adding a Finishing Process.

3.3.3 Database

The database is the third element of the developed AMDSS. The database used here consists of five tables: process table, material table, machine table, finishing options table and intermediate material table.

The process table contains the following fields: ID, process name, wall thickness, accuracy, surface finish, Max X, Max Y, Max Z and quantity. The process selection, the browsing specific process module, the ranking by SMART method and the process update use this table to get and send the required information from and to it.

The Material table contains the following fields: ID, process name, material name, tensile strength, tensile modulus, hardness, heat deflection temperature, sanitary conditions, color, density, heat resistance, water resistance, and dielectric strength. The material selection, the browsing specific material module, the ranking by SMART method and the material update use this table to get and send the required information from and to it.

The machine table contains the following fields: ID, process name, machine name, build envelope, and layer thickness. The machine selection and the machine update use this table to get and send the required information from and to it.

The finishing options table contains the following fields: ID, process name, and the finishing method name. The finishing options selection and the finishing methods update use this table to get and send the required information from and to it.

Finally, the intermediate material table contains the same fields as the material table. The intermediate material selection and the intermediate material update use this table to get and send the required information from and to it.

The developed database contains 13 different processes, 133 different materials, 10 intermediate materials and 49 finishing methods. The information was collected through vendors' websites and service bureaus' recommendations.

ID	Process	Wall thickness	Accuracy	Surface Finish	Max X	Max Y	Max Z
1	#SLA#REACTION INJECTION MOULDING	VERY-THIN	TIGHT	GOOD-AVERAGE	650	750	550
2	#EBM	THIN-AVERAGE	TIGHT	EXCELLENT	500	500	300
3	#LENS	THIN-AVERAGE	TIGHT	EXCELLENT	300	300	300
4	#LASER CUSING	THIN-AVERAGE	TIGHT	EXCELLENT	500	500	300
5	#3DP	AVERAGE-WIDE	LOOSE	AVERAGE-ROUGH	500	500	300
7	#SLA	VERY-THIN	TIGHT	EXCELLENT	650	750	550
8	#SLS	THIN-AVERAGE	AVERAGE	GOOD-AVERAGE	2250	1550	2100
9	#FDM	AVERAGE-WIDE	AVERAGE	GOOD-AVERAGE	914	614	914
10	#SLA#INV.CASTING	VERY-THIN	TIGHT	EXCELLENT	650	750	550
11	#SLA#SILICONE TOOLING#VACUUM CASTING	AVERAGE-WIDE	TIGHT	GOOD-AVERAGE	650	750	550
22	#POLYJET	AVERAGE-WIDE	TIGHT	GOOD-AVERAGE	500	400	200
23	#Laminated Object Modelling LOM	AVERAGE-WIDE	LOOSE	AVERAGE-ROUGH	400	600	400
25	#SLM	THIN-AVERAGE	AVERAGE	GOOD-AVERAGE	123	123	80

Figure 3.43: Database Screen Shot.

Entity Relationship Diagram (ERD)

One important advantage about database is relationships between records which ensure data integrity. To understand these relationships a data modeling diagram called entity relationship diagram (ERD) is shown in Figure 3.44. The ERD is a graphical representation of how the records within the table deal with each other. The software used to draw the ERD was graphical software called Microsoft Visio. The fields in each table are also called entities. For example, the entities in the process table are: ID, process name, wall thickness, accuracy, surface finish, Max X, Max Y, Max Z and quantity. Each table has a primary key (PK) which is a key that uniquely identify a single entity instance (it cannot be repeated). The primary key in process table is the process name For example if a user enters a new record for process field such as (#SLS) that is already present in the database this new record will not be accepted in the database because the process entity is a primary key. For all other tables (materials, intermediate materials, machines and finishing) the primary key is an ID which is an automatic number that is automatically generated for each new record. If a primary key of a certain table is

presented in another table it is called foreign key (FK). Each table could have multiple foreign keys. The process name is a primary key in the process table and a foreign key in all the other tables. Any changes that occur in one table will occur in all the other tables. For example, if a process is added or deleted or altered in one table the change will affect all the other tables. Another issue that ensures the integrity between the tables is the type of relationships between them. The possible relationships are: one-to-one, one-to-many and many-to-many. One-to-one relationship means the record in table A could only be repeated once in table B, the one-to-many relationship means that the record in table A could be repeated several times in table B but not vice versa and the many-to-many relationship means that the record in table A could be repeated in table B and vice versa. The relationships between the process table and all other tables are one-to-many. The process name can be repeated several times in any of the tables, which means that one process could have many machines, many materials, many intermediate materials and many finishing methods.

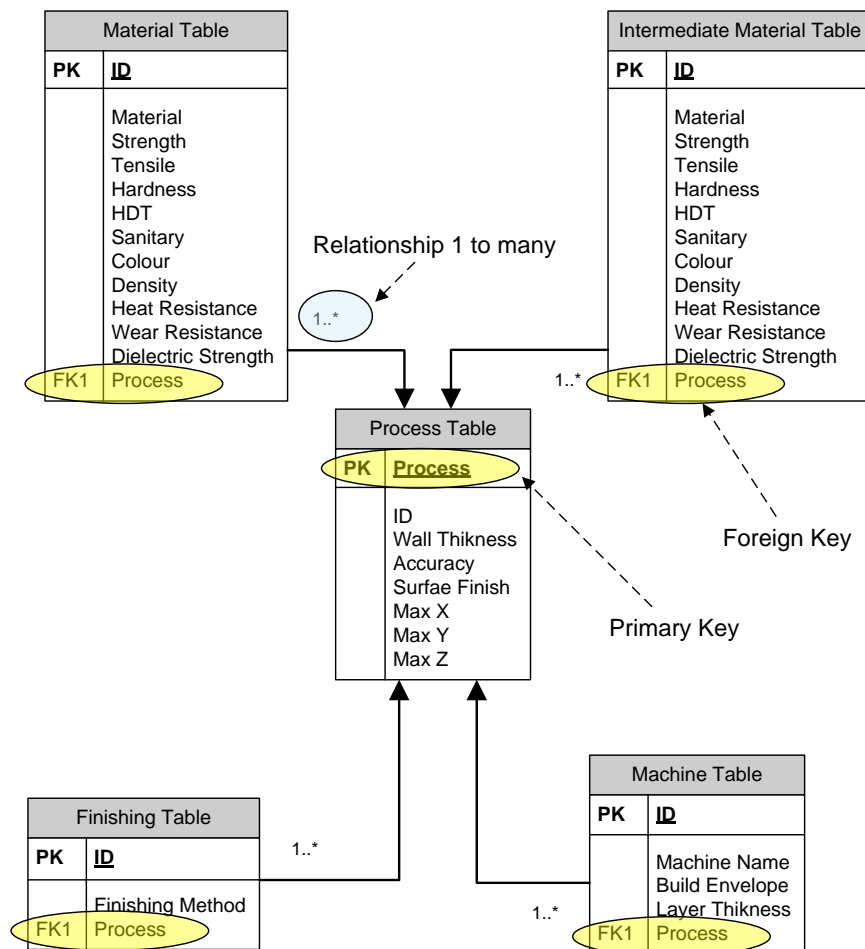


Figure 3.44: Entity Relationship Diagram (ERD).

3.4 Discussion

This chapter has discussed the additive manufacturing decision support system (AMDSS) design and development. To develop the system nine steps were used. The third and fourth steps were discussed in this chapter. Step three focuses on identifying system target specifications. Step four focuses on developing the system. Different architectures of the system were considered and knowledge based system (KBS) + database (DB) architecture was selected because it could meet all the system target specifications.

One of the important points that helped to have an updatable customizable system is the flexible IF-then rules used within the KBS system. The conditions of the IF-then are based on variables and not constant values. Consequently, each time a user uses the system and the values of the variables change, the rule gives a different output. This flexibility gives the developed system an updatability characteristic that prevents it from being obsolete after a while.

Chapter 4. Verification and Validation

This chapter explains how the verification and the validation of the developed AMDSS were carried out. The verification was done through checking the logic of the developed system. For validation, three industrial case studies were used. The selection of the processes, materials, finishing methods and machines for these three case studies was done in consultation with experts and service bureaus. In addition, the same inputs for the three case studies are fed to the AMDSS. The outputs of the AMDSS are compared with selections made with in consultation with experts to assess how well the system work.

4.1 Verification

Before using the developed AMDSS, it has to be tested and verified. The aim of the verification is to make sure that the developed system is working properly. The verification was done through several ways.

First, while building the system, the system logic is checked at each stage before moving to the next one. In addition, after the system had been completely developed, the whole system was checked to make sure that the system was working properly all together.

Some scenarios were applied to the system to test the input-output relationships and the system performance when subjected to inputs change. To test the process selection stage, some process inputs like size, quantity, surface finish, minimum wall thickness and accuracy level were determined and the AMDSS retrieved the AM processes that satisfy these inputs. The same inputs are retrieved manually from the database. The process outputs from the ADMSS are compared to those manually retrieved. As an example of one of the scenarios, the following inputs were used:

- Minimum wall thickness = thin-average
- Accuracy = average
- Surface finish = good-average
- Quantity = 1

- Length = 300 mm
- Width = 300 mm
- Height = 100 mm

The outputs determined by examination of the data (which were the processes that could manufacture the part) were:

- EBM
- Laser Cusing
- LENS
- SLA
- SLA+ Investment Casting
- SLA+ Reaction Injection Molding
- SLS

The results retrieved from the AMDSS and manually retrieved from database were exactly similar. When changing these inputs, the outputs also change. This checking process was carried out several times to assure that the AMDSS retrieving logic of the process selection was correctly programmed. The same testing method was done to the material selection stage and the outputs of AMDSS were compared to those retrieved manually from the database. As an example, using the same process inputs mentioned above, some material requirements were used:

- Strength = 100 MPa
- Tensile = 5000 MPa

The outputs determined by examination of the data (which were the materials that could be used to manufacture the part within the previously selected process) were shown in Table 4-1.

Process Name	Material	Strength	Modulus
#SLA#INV.CASTING	A 201 (A12010)	427	74600
#SLA#INV.CASTING	354 (A03540)	345	76700
#SLA#INV.CASTING	C90710	390	82000
#SLA#INV.CASTING	C86500	838	103000
#SLA#INV.CASTING	G10500	705	216000
#SLA#INV.CASTING	ASTM CF-20	580	199000

Table 4-1: An Example of Results Retrieved from a Verification Scenario.

It has to be mentioned that some providers of some metal fabrication processes such as EBM, Laser Cusing and LENS do not provide complete datasheets for their materials. For this reason, their materials were not listed because the strength or the tensile information was not available in the database.

The results retrieved from the AMDSS and manually retrieved from database were exactly similar. When changing these inputs, the outputs also change. This checking process was carried out several times to assure that the AMDSS retrieving logic of the material selection was correctly programmed.

In addition, to test the manufacturability evaluation and the capability analysis, some process inputs that are known to not be able to be manufactured using additive manufacturing technology were fed to the system and then the system checked for the correct reasons being provided. As an example of one of the scenarios, the following inputs were used:

- Minimum wall thickness = thin-average
- Accuracy = average
- Surface finish = excellent
- Quantity = high
- Length = 3000 mm
- Width = 3000 mm
- Height = 2000 mm

The output of the AMDSS was that no possible processes could meet your required process inputs because of the following reasons:

- No AM process within the database can meet your required length (X).
- No AM process within the database can meet your required length (Y).

The results retrieved from the AMDSS and manually retrieved from database were exactly similar.

The same method was applied to the material properties evaluation and capability analysis. For example, a required strength of 3000 MPa is fed to the AMDSS and the output was that:

- No AM process within the database can meet your required strength.

When checking this manually in the database it can be noticed that the maximum strength available is 1430 MPa.

The comparison between the outputs of the manual retrieving from the database and the ADMSS outputs for different stages was done throughout the development so that errors were corrected immediately. These scenarios verify that the model is working correctly and logically.

Furthermore, the calculations of the ranking of the SMART method have to be tested. This is done though calculating using spreadsheets and comparing the results with the AMDSS results. Gaining the same results proved that the logic of the SMART method was used correctly within the developed system.

4.2 Validation

The main purpose of the validation process was to test that the developed system gives realistic and technically feasible answers to the users and to assure that the additive manufacturing selection knowledge and expertise were captured and built correctly within the developed system. It means that the selections of the process chains, materials, intermediate materials, finishing methods and machines made by the AMDSS conform to the same selections made by a service bureau or an expert user. To achieve this, three industrial case studies were chosen and the selection of all the needed parameters done with the consultation of AM experts. These three case studies were manufactured according to the selection so that the tangible products can assure the compatibility to the user inputs. In addition, capturing the knowledge needed for the additive manufacturing decision support

system was not only done by asking the experts and the service bureaus, but also by learning from experimental work. The three case studies were fed to the AMDSS and the outputs were compared to the real life decisions that were made with consultation with the AM experts. Next sections explain the case studies in detail.

4.2.1 *Razor Blade Case Study*

The first case study was a part consisting of smaller components assembled together to form a disposable razor blade. The reason the factory needs to manufacture this part is to have a functional prototyping for testing. Figure 4.1 shows STL file of one of the required parts called guard bar. The STL file was sent to the additive manufacturing machine so the part can be made.

The experimental work

Different small parts are assembled together to form a disposable razor blade. Figure 4.2 shows the different small components made using selective laser sintering technology (SLS) in Nylon (trade name Duraform) using a 3D Systems SLS machine at the Keyworth Institute, University of Leeds. Also these parts were made using fused deposition modeling technology (FDM) in ABS material using an FDM machine in Newcastle University. Both technologies did not show satisfactory results according the accuracy and surface finish required by the user. The first lesson taught from this case study is that the small wall thickness and the very tight accuracy are difficult to achieve using the both used technologies. Furthermore, experts confirm that this rule applies to most of additive manufacturing technologies.

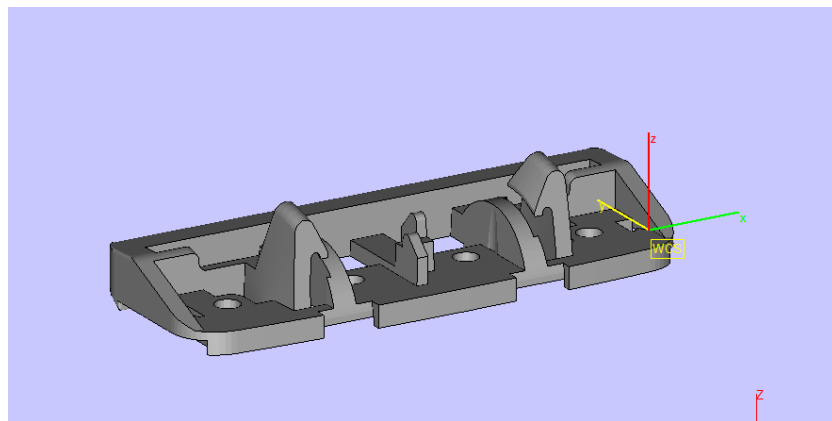


Figure 4.1: Guard Bar Part.



Figure 4.2: Razor Case Study Manufactured Parts.

Selecting using AMDSS

To validate the developed AMDSS, the case study information was fed to the system and the output was compared to the real life application. Table 4-2 shows the part information.

Part Requirements		Material	
Length (mm)	39.6	Strength (MPa)	50
Width (mm)	10.56		
Height (mm)	5.9		
Minimum Wall Thickness (mm)	Very Thin (0.5 mm)		
Accuracy (mm)	Tight <0.1 mm		
Surface Finish Ra	Good-Average (4 μm)		
Quantity	1		

Table 4-2: Part and Material Requirements for the Top Cap.

When the part information was fed to the system, the output was the screen shown in Figure 4.3 indicating that there is a concern about the quality of the product because of the accuracy is tight and the wall thickness is very thin. The user has three options: to accept this notice and continue with the system or to end the program because additive manufacturing is not a solution for this case or to get back and change some of the part information regarding accuracy and surface finish. Because both accuracy and surface finish were important for this case study, the user decided to terminate the system understanding that additive

manufacturing is not the right answer for his case. The AMDSS selections conformed to selections made in consultations with experts. The user did not select any AM process because there was not one that could satisfy their needs. The same result was given by the AMDSS.



Figure 4.3: AMDSS Output for the Guard Bar Part.

4.2.2 *Automotive Case Study (1)*

The second case study was an automotive spare part. It is split into two parts to be used as indirect patterns for sand casting to produce a pressure plate of a car clutch. Figure 4.4 and Figure 4.5 show the first and second parts respectively.

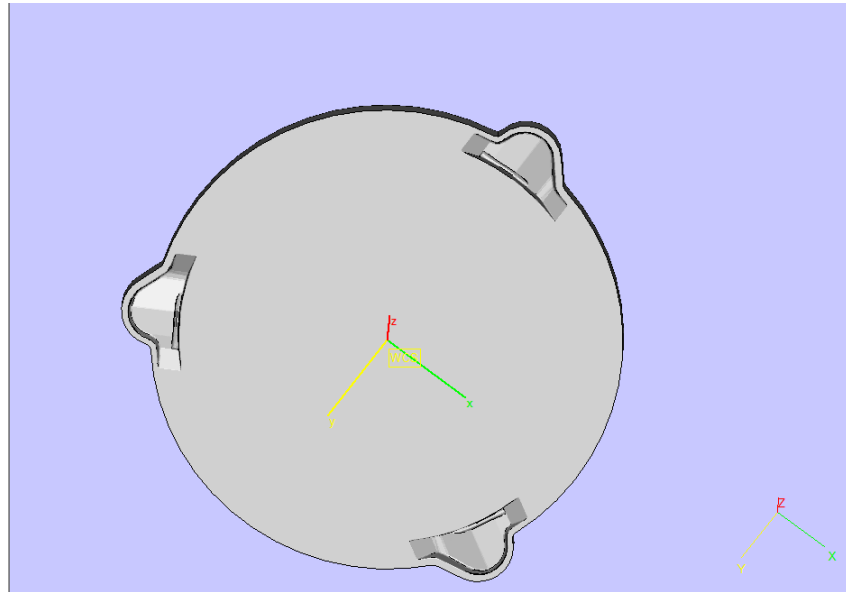


Figure 4.4: The First Part of the Automotive Case Study 2.

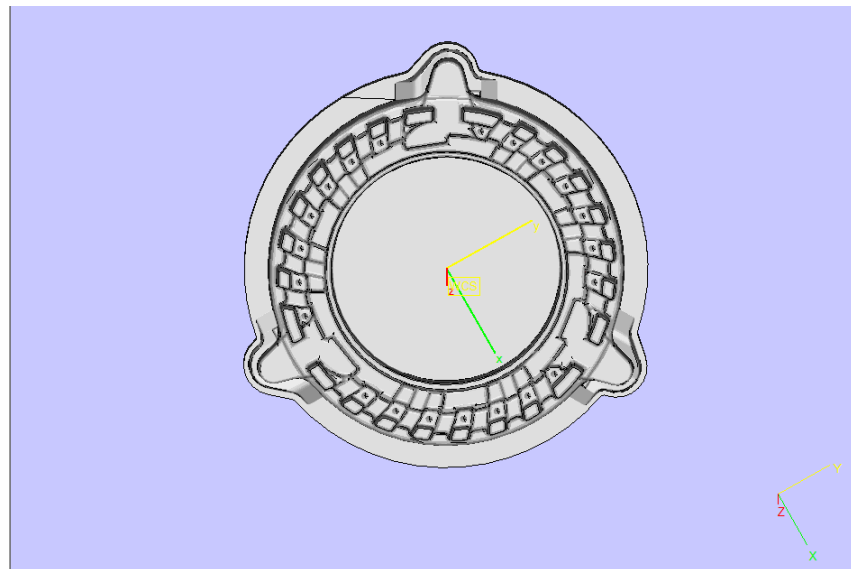


Figure 4.5: The Second Part of the Automotive Case Study 2.

The experimental work

To manufacture the patterns a rapid tooling process that consists of three stages was proposed by Ghazy et al. (2010). The first stage was to build the pattern model using an additive manufacturing system. The second stage was to cast epoxy resin into the pattern to create the mould. The final stage was to cast epoxy resin into the mould to create the pattern.

The proposed rapid tooling process was applied to the automotive case study as follows: in the first stage of the process the AM patterns were made in Nylon

(trade name Duraform) using a 3D Systems SLS machine at the Keyworth Institute, University of Leeds. Figure 4.6 shows the produced patterns.



Figure 4.6: Rapid Tooling Patterns.

In the second stage an epoxy resin mould was created. Furthermore, sand paper was applied to the produced mould to improve the surface finish. Finally, the third stage was also applied; the epoxy resin was poured into the mould to produce the required pattern. Figure 4.7 shows the final product after the sand casting process.

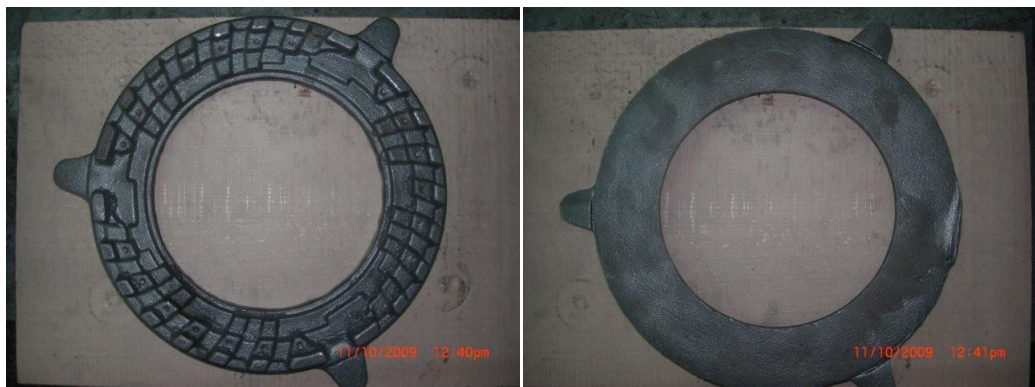


Figure 4.7: The Final Products after Casting.

Selecting using AMDSS

When the part requirements shown in Table 4-3 were fed to the system, the AMDSS retrieved the possible processes or process chains that could do the job and listed them. The retrieved processes (single processes or process chains) were:

- EBM
- FDM
- Laser Cusing
- LENS
- SLA
- SLA + Investment casting
- SLA + Silicone tooling + Vacuum Casting
- SLA + Reaction Injection Molding
- SLS

Part Requirements		Material Requirements	
Length (mm)	230	Strength (MPa)	40
Width (mm)	245		
Height (mm)	H1 = 10 H2 = 25		
Minimum Wall Thickness (mm)	Average wide (2 mm)		
Accuracy (mm)	Average= 0.20 mm		
Surface Finish Ra	Average Rough (18 μ m)		
Quantity	1		

Table 4-3: Part and Material Requirements for the Two Parts of Automotive Case Study 1.

The next step was the material requirements step. The user entered the material requirements shown in Table 4-3 for the parts. The material requirement in this case is the tensile strength equals 40 MPa. Figure 4.8 shows the possible processes and materials that can manufacture this part. The user presses the next button, so the criteria screen appears as shown in Figure 4.9. Because the strength was important in this case, so the user gave weight of eight to it. Figure 4.10 shows the

final ranking screen. The first alternative was SLA process and DMX-SL100 material with the highest score of 42. This score was calculated with the SMART method and depended on the user weights'. If the weights were changed, the score and consequently the order would have been changed. The user selected the SLS process and the PA2200 material. Next, the user selected the finishing options which was sanding as shown in Figure 4.11. The user can also select the machine. Finally, the technical summary as shown in Figure 4.12 summarized the user selections. The AMDSS selections conformed to selections made in consultations with experts. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 4.10 because there are other factors that affect the selections such as price given by service bureau and the availability of processes and materials.

	MATERIAL	PROCESS	MATERIAL	STRENGTH	MODULUS	HARDNESS	DENSITY	DIELECTRIC STRENGTH	HDT
1	1 #SLA		WATERSHED 11120	54	2800	0	1	3	54
2	2 #SLA		NANO TOOL	78	11400	94	2	3	225
3	3 #SLA		SOMOS PROTOCAST AF 19120	55	2540	86	1	3	58
4	4 #SLA		PROTO THERM 2120	77	3250	87	1	3	146
5	5 #SLA		PROTP THERM 12110	66	2950	86	1	3	53
6	6 #SLA		PROTOGEN 18920	70	2623	88	1	3	96
7	7 #SLA		PROTOGEN 18120	69	2900	88	1	3	97
8	8 #SLA		WATERSHED 11110	48	2640	0	1	3	47
9	10 #SLA		PROTOCAST AF 19122	45	2187	86	1	3	59
10	11 #SLA		WATERCLEAR 10110	43	2040	83	1	3	51
11	12 #SLA		PROTOGEN 18420	68	2960	87	1	3	98
12	13 #SLA		NANOFORM 15120	53	5900	92	1	3	269
13	14 #SLA		WATERSHED XC11122	54	2880	0	1	3	54
14	15 #SLA		WATER CLEAR ULTRA 10122	56	2900	87	1	3	61
15	19 #SLA		SOMOS 7129 EPOXY PHOTOPOLYMER	44	2598	88	1	3	97
16	20 #SLA		SOMOS 7110 EPOXY PHOTOPOLYMER	69	2413	85	1	3	89
17	21 #FDM		UTLEM 9085	72	2220	0	1	3	153
18	22 #FDM		PC-ISO	57	998	0	1	3	133
19	23 #FDM		PC-POLYCARBONATE	68	2280	90	1	3	138
20	24 #FDM		PPSF	55	2068	100	1	3	189
21	25 #FDM		PC-ABS	41	1917	90	1	3	110
22	31 #FDM		PC	68	2500	0	1	3	138
23	32 #SLS		PA 2200 TOP SPEED	45	1600	75	1	3	150
24	34 #SLA		ACCURA 50	50	2690	86	1	3	80
25	35 #SLA		SOMOS PROTOCAST AF 19120	55	2540	86	1	3	58
26	37 #SLA		ACCURA BLUESTONE	68	11700	92	2	3	284
27	38 #SLA		ACCURA ACCUGEN	67	3030	82	1	3	0
28	39 #SLA		ACCURA 60	68	3100	86	1	3	56

Figure 4.8: List of the Possible Processes and Materials for Automotive Case Study 1.

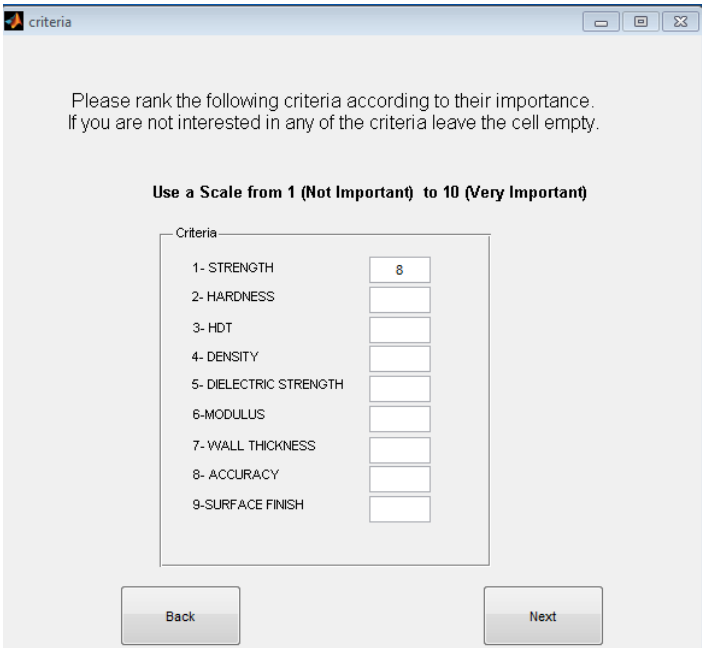


Figure 4.9: Criteria Weighting for Automotive Case Study 1.

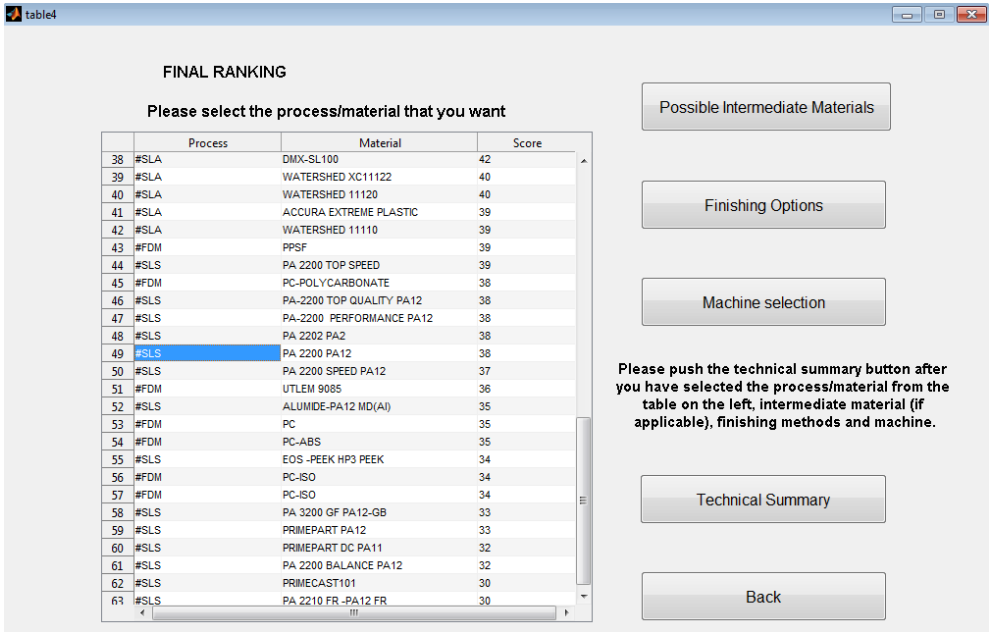


Figure 4.10: Final Ranking Screen for Automotive Case Study 1.

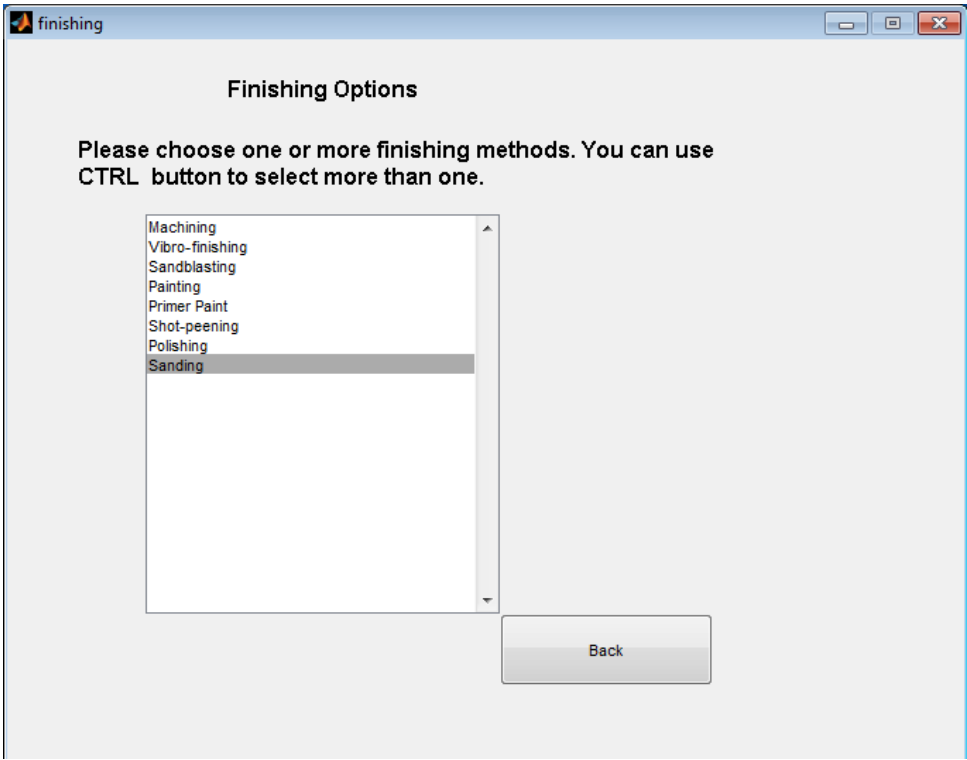


Figure 4.11: Choosing Finishing Methods for Automotive Case Study 1.

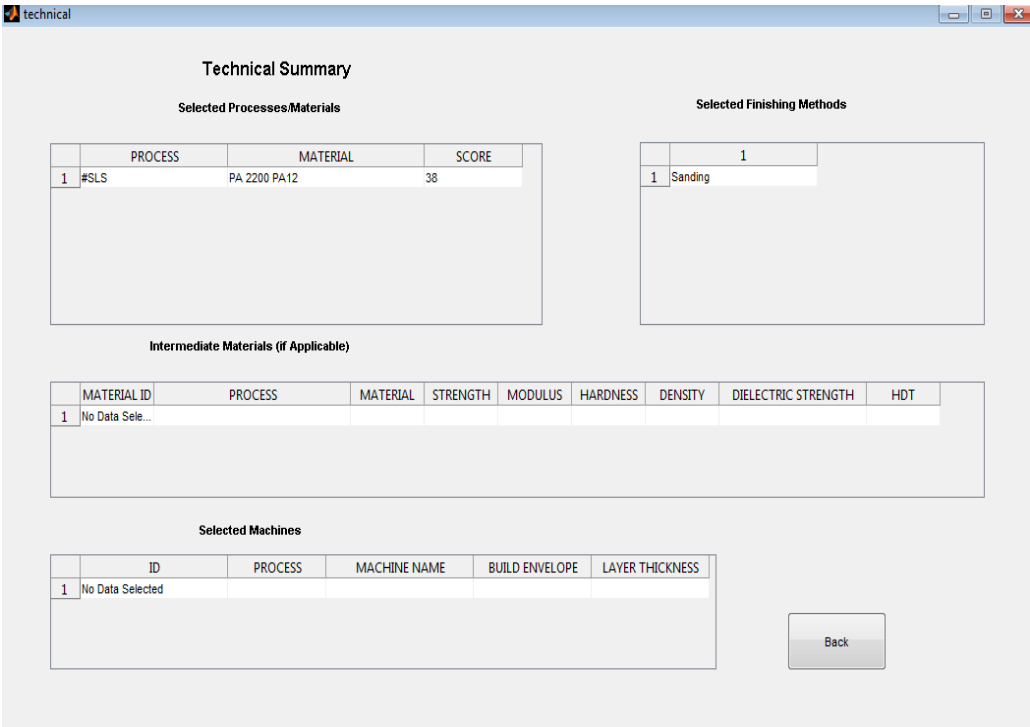


Figure 4.12: The Technical Summary Screen for Automotive Case Study 1.

4.2.3 Automotive Case Study (2)

The third case study was an automotive spare part too, and it was split into two parts to be used as patterns for sand casting to produce rear axle brake housing (Ghazy et al.,2011). Figure 4.13 and. Figure 4.14 show the first and second parts respectively.

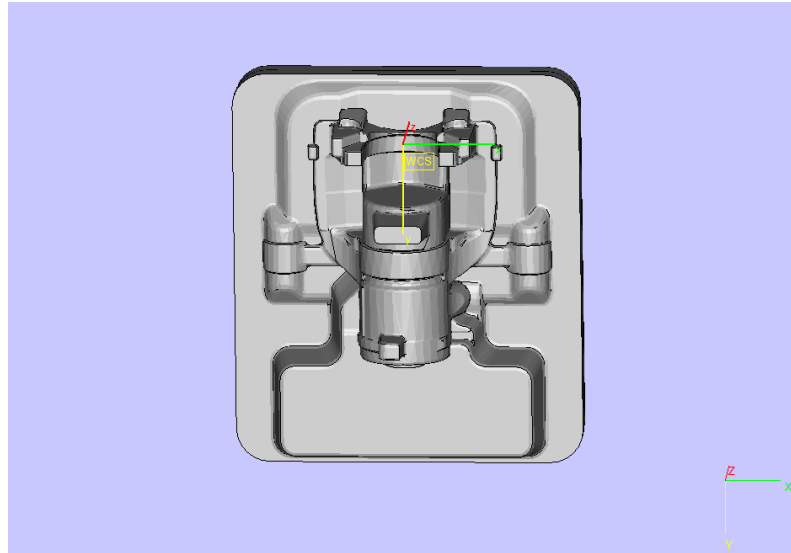


Figure 4.13: The First Part of the Automotive Case Study 2.

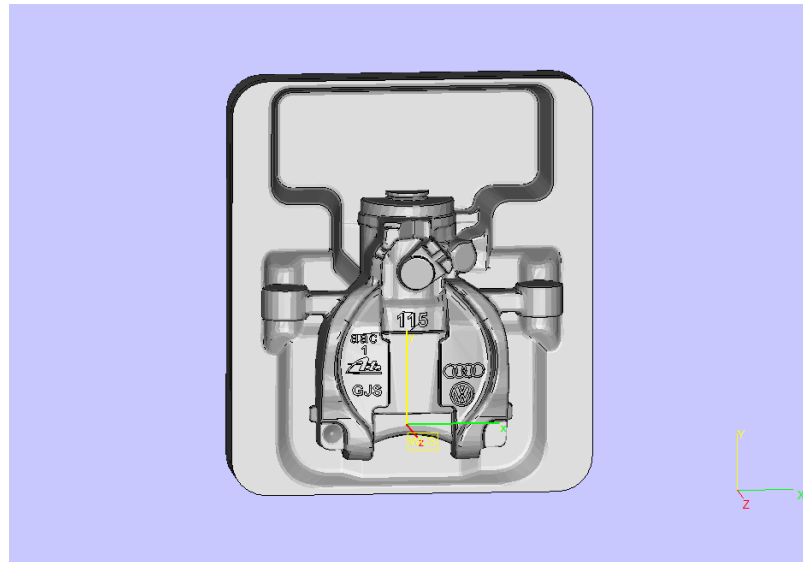


Figure 4.14: The Second Part of the Automotive Case Study 2.

The experimental work

The patterns were fabricated using SLS technology in polyamide material and finished using filler and sanding process. The following steps were applied: 1- manufacturing the parts using SLS technology from polyamide material, Figure 4.15 shows the SLS fabricated patterns, 2- applying the plastic filler to the parts,

3- smoothing the parts using sand papers. The Ra for the first pattern was 16.47 μm and the Ra for the second pattern was 19.69 μm . These values were acceptable for the sand casting patterns and 4- starting the sand casting process Figure 4.16 shows the pictures of the casted products.



Figure 4.15: SLS Fabricated Patterns.



Figure 4.16: The Castings.

Selecting using AMDSS

Because the patterns were going to be applied to heat and pressure of the sand casting process, the user chose to have strength equals 50 MPa and heat deflection temperature (HDT) equals 80 °C. When the part requirements shown in Table 4-4 for the first and the second parts were fed to the system, the AMDSS retrieved the possible processes that could do the job and listed them which were:

- EBM
- FDM
- Laser Cusing

- LENS
- SLA
- SLA+ Investment casting
- SLA+ Silicone tooling +Vacuum Casting
- SLS

Part Requirements		Material Requirements	
Length (mm)	205	Strength (Mpa)	50
Width (mm)	236	Heat Deflection Temp	80
Height (mm)	H1 = 94.36 H2=54.10		
Minimum Wall Thickness (mm)	Average wide (2 mm)		
Accuracy (mm)	Average= 0.20 mm		
Surface Finish Ra	Average Rough (18 μ m)		
Quantity	1		

Table 4-4: Part and Material Requirements for the Two Parts of Automotive Case Study 2.

The next step was the material requirements step. The user entered the material requirements shown in Table 4-4. Figure 4.17 shows the possible processes and materials that can manufacture this part. The user pressed the next button, so the criteria screen appeared as shown in Figure 4.18. Because the strength and the heat deflection temperature were important in this case, so the user gave weight ten to both of them. Figure 4.19 shows the final ranking screen. The first alternative was SLA process and Accura Bluestone material with the highest score of 256. This score was calculated with the SMART method and depended on the user weights'. If the weights were changed, the score and consequently the order would have been changed. The User selected the SLS process and the PA2200 material. Next, the user selected the finishing options which were vibro-finishing and sanding as shown in Figure 4.20. The user selected the machine to be EOS P730. Finally, the technical summary as shown in Figure 4.21 summarized the user selections. The AMDSS selections conformed to selections made in consultations with experts. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 4.19 because there are other factors that affect the selections such as price given by service bureau and the availability of processes and materials.

	MATERIAL	PROCESS	MATERIAL	STRENGTH	MODULUS	HARDNESS	DENSITY	DIELECTRIC STRENGTH	HDT
1	2 #SLA		NANO TOOL	78	11400	94	2	3	225
2	4 #SLA		PROTO THERM 2120	77	3250	87	1	3	146
3	6 #SLA		PROTOGEN 18200	70	2623	88	1	3	98
4	7 #SLA		PROTOGEN 18120	69	2900	88	1	3	97
5	12 #SLA		PROTOGEN 18420	68	2960	87	1	3	98
6	13 #SLA		NANOFORM 15120	53	5900	92	1	3	269
7	20 #SLA		SOMOS 7110 EPOXY PHOTOPOLYMER	69	2413	85	1	3	89
8	21 #FDM		UTLEM 9085	72	2220	0	1	3	153
9	22 #FDM		PC-ISO	57	998	0	1	3	133
10	23 #FDM		PC-POLYCARBONATE	68	2280	90	1	3	138
11	24 #FDM		PPSF	55	2068	100	1	3	189
12	31 #FDM		PC	68	2500	0	1	3	138
13	34 #SLA		ACCURA 50	50	2690	86	1	3	80
14	37 #SLA		ACCURA BLUESTONE	68	11700	92	2	3	284
15	40 #SLA		ACCURA 45HC	61	2960	87	1	3	103
16	43 #SLA		ACCURA 48HTR	67	3980	86	1	3	130
17	44 #SLA		ACCURA 50	50	2690	86	1	3	80
18	51 #FDM		PC-ISO	57	998	0	1	3	133
19	68 #SLA		ACCURA 40	61	3321	84	1	3	114
20	80 #SLS		PA-2200 TOP QUALITY PA12	52	1850	75	0.9300	0	150
21	81 #SLS		PA-2200 PERFORMANCE PA12	50	1800	75	0.9300	0	150

Figure 4.17: List of the Possible Processes and Materials for Automotive Case Study 2.

Please rank the following criteria according to their importance. If you are not interested in any of the criteria leave the cell empty.

Use a Scale from 1 (Not Important) to 10 (Very Important)

Criteria

- 1- STRENGTH
- 2- HARDNESS
- 3- HDT
- 4- DENSITY
- 5- DIELECTRIC STRENGTH
- 6-MODULUS
- 7- WALL THICKNESS
- 8- ACCURACY
- 9-SURFACE FINISH

Back Next

Figure 4.18: Criteria Weighting for Automotive Case Study 2.

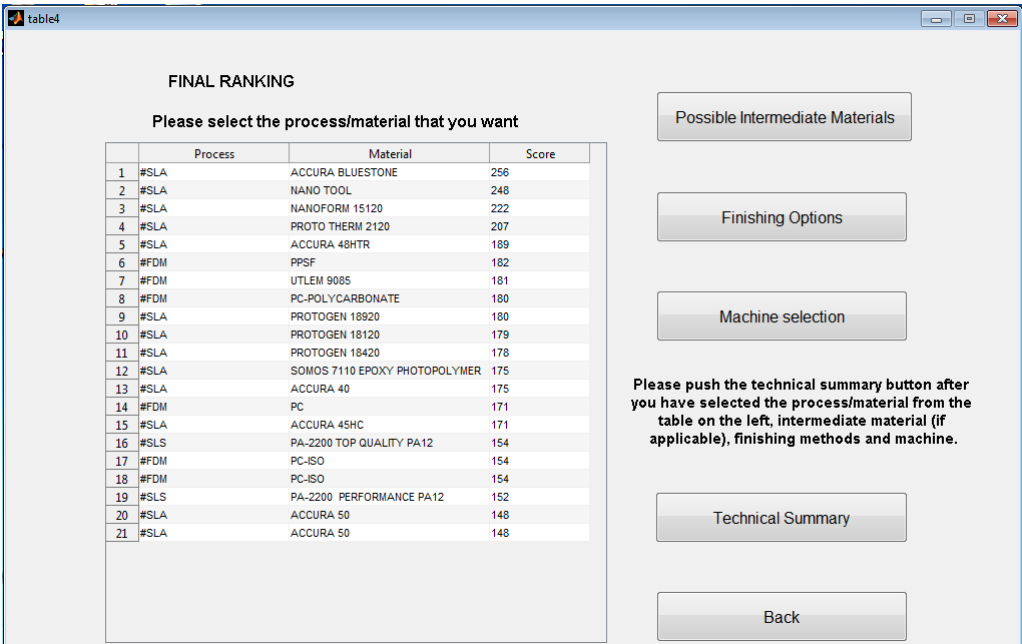


Figure 4.19: Final Ranking Screen for Automotive Case Study 2.

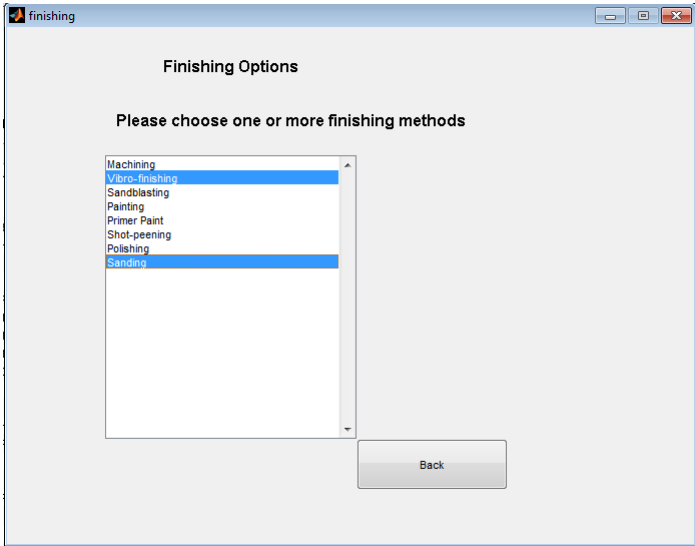


Figure 4.20: Choosing Finishing Methods for Automotive Case Study 2.

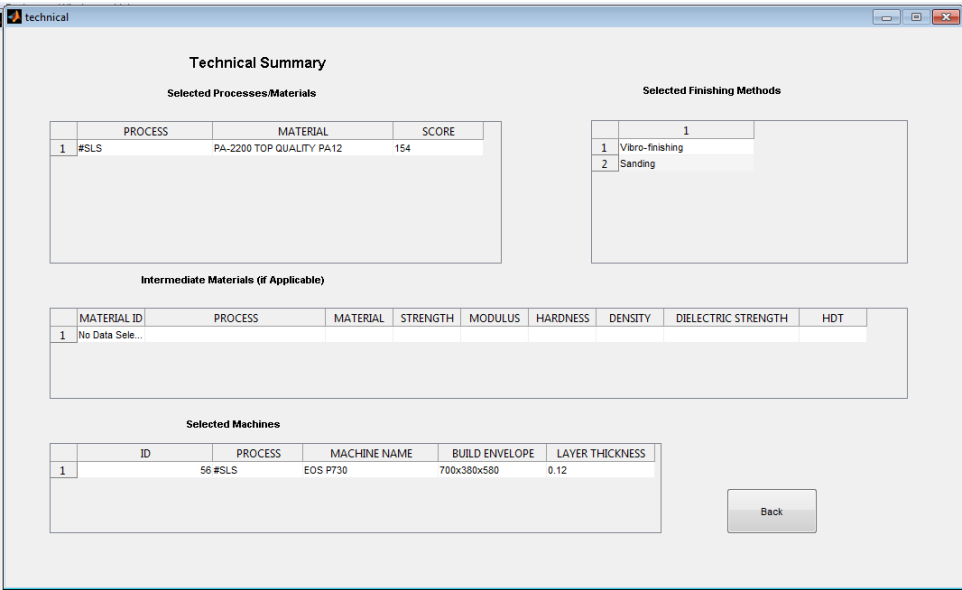


Figure 4.21: The Technical Summary Screen for Automotive Case Study 2.

4.3 Discussion

To conclude, the verification process has proven that the developed system logic is correct. The three case studies have helped in the validation process and also have allowed the researcher to understand some concepts of additive manufacturing technologies. The first lesson from case study one, showed that the small features and the high level of quality together is difficult to be achieved using additive manufacturing. The second lesson from case study two and three showed that the selections made were not the best technically because cost factor was taken into consideration. This showed a limitation in the developed ADMSS, which is that the cost not included.

The case studies, by giving some lessons and underlining some AMDSS limitations, showed a strong need that focusing on the users and testing the system with them will give positive important feedback. The next chapter will test the AMDSS with some users to obtain the feedback to understand the limitations of the developed system, so further development can be done to finally have a better system. Furthermore, most of the research done before in the additive manufacturing selection area did not focus on the user or the customer. Developing an additive manufacturing decision support system that includes the user is one of this research objectives and contributions.

Chapter 5. User Feedback and Evaluation

A major drawback of many AM selectors is that they do not represent users and they only show the point of view of their developers. To overcome this problem in the developed AMDSS, one of the target specifications is to be a user focused system. Obtaining feedback from users is the sixth step of the AMDSS development steps discussed in chapter three and this chapter explains how this was achieved. Furthermore, four users tested the developed AMDSS with four products by comparing the selections of the system for these products to their previously made selections.

5.1 User Feedback

There are three types of interviews (Myers and Newman,2007):

- 1- Structured interview in which the interviewer uses a set of rules and questions that cannot be changed across all interviewees.
- 2- Semi-structured interview in which the interviewer could add questions or ask for clarifications or make explanations.
- 3- Non-structured interview which is a general discussion between the interviewer and the interviewee rather than a formal interview.

In this study, the feedback from users was obtained using a semi-structured interview. This type was selected because it combines structural organization of the questions with flexibility. It gives the interviewer the possibility of explaining to interviewees different aspects of the system developed and asking about their opinions.

The interview starts by giving an outline to the user at the developed AMDSS, and explaining the different sections of the questionnaire. Next, the interviewee thinks of a product that he would like to manufacture using AM technologies and starts using the AMDSS and answers the questions. Some of the interviewees asked to review some of the screens while answering the questions. Each interview took approximately from forty five minutes to one hour.

5.1.1 *Questionnaire Design*

The questionnaire was designed to collect information from users in an organized way. It consisted of three parts:

- 1- User profile. It gave the researcher an overview of user's knowledge about AM technologies and processes.
- 2- AMDSS screens. It asked users about the terminology used and the information presented in the main screens
- 3- General questions. It gave information about the overall system performance by asking users about the advantages and the limitations of the system.

Thirteen users responded to the questionnaires. They were classified into two groups: advanced users and average users. The advanced users are technology experts who work for service bureaus or deal with AM technologies on regular basis in research centers. The average users are inexperienced users that have from little to average experience in the AM field.

According to this classification four advanced users and nine average users responded to the questionnaire. The questionnaire is shown in Table 5-1, Table 5-2, Table 5-3, Table 5-4, Table 5-5 and Table 5-6.

Additive Manufacturing Decision Support System (AMDSS) Feedback

1- User profile

Question 1:

How often do you need to select additive manufacturing process or material?

- a. Weekly
- b. Monthly
- c. Sporadically
- d. Other: _____

Question 2:

Have you used any knowledge based system for selecting additive process or material before? If yes please name it.

Question 3:

How do you normally select the following:

- a. Additive manufacturing process
- b. Material
- c. Finishing methods
- d. Machines

2- AMDSS Screens

Question 1: Process screen

i. Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Table 5-1: AMDSS First Version Questionnaire (Page 1 of 6).

ii. Terminology Section

1- Do you think that the terminology used in the following drop down menu is easy to understand? Use the scale give below each term.

[1= difficult to understand and 5 =easy to understand.]

- Min wall thickness

(Very-Thin 0-0.5mm) / (Thin-Average 0.5-2mm) / (Average-Wide (0.2mm)

1	2	3	4	5
---	---	---	---	---

- Accuracy

(Loose <0.1mm) / (Average 0.1-0.25mm) / (Tight>0.25mm)

1	2	3	4	5
---	---	---	---	---

- Surface Finish

(Average-Rough>12.5 um) / (Good-Average 3.2-12.5 um) / (Excellent 0-0.32 um)

1	2	3	4	5
---	---	---	---	---

- Quantity

(One) / (Low2-20) / (Medium 20-25) / (High>50)

1	2	3	4	5
---	---	---	---	---

If you think the terminology is difficult to understand please suggest alternative phrasing.

Question 2: Material properties screen

i. Information Section

- Do you think that the information required is appropriate?
- For your application, do you have data for all the presented fields?
- Are there any fields that you would remove?
- Are there any fields that you would add?

Table 5-2: AMDSS First Version Questionnaire (Page 2 of 6).

ii. Screening Method Section

1- Do you prefer the material screening method to be :

- a. A generalized screening method like by selecting material class (Metals, Plastics, Ceramics, Composites, Wood. .etc)
- b. A properties screening method by giving values to one or more material properties.
- c. I would like to choose every time I make a selection between the two screening methods.

2- According to the material properties screening method do you think that it should be based on:

- a. Minimum values.
- b. Maximum values
- c. Both

Question 3: Criteria weighting screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Question 4: Final ranking screen

Scoring Results Section

- a. Are the scoring results clear and understandable? If no please comment.
- b. Would you add or remove any information presented?

Table 5-3: AMDSS First Version Questionnaire (Page 3 of 6).

Question 5: Process update screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Question 6: Material update screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Question 7: Machine update screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Question 8: Finishing options update screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Table 5-4: AMDSS First Version Questionnaire (Page 4 of 6).

3- General Questions

Question 1:

The Decision Support System (DSS) has been designed to choose process first than material. Do you think that this is appropriate? Please comment on your answer.

Question 2:

Did you find the choice of the finishing methods that you want useful? Please comment.

Question 3:

Did you find the DSS helpful when you have applied it to your case study for selecting:

- i. The possible processes chains.
- ii. Materials
- iii. Machines
- iv. Finishing methods

Question 4:

When the DSS indicates that the part cannot be made using additive manufacturing process, is the information provided clear?

Question 5:

When the DSS indicates that the part cannot be made using additive manufacturing material, is the information provided clear?

Question 6:

Did you find that the DSS provides sufficient information on the ranking and the choices?

Question 7:

How important is the ability of updating the process chain, material, finishing and machines in an additive manufacturing DSS?

Table 5-5: AMDSS First Version Questionnaire (Page 5 of 6).

- a. Not Important
- b. Important
- c. Very Important
- d. Extremely Important

Question 8:

What elements do you like to add in the DSS?

Question 9:

What did you like most?

Question 10:

What did you dislike most?

Question 11

How do you rate the following elements in the DSS:

Elements	Rating				
Process selection	Weak	Fair	Good	Very Good	Excellent
Material selection	Weak	Fair	Good	Very Good	Excellent
Intermediate material	Weak	Fair	Good	Very Good	Excellent
Finishing selection	Weak	Fair	Good	Very Good	Excellent
Machines selection	Weak	Fair	Good	Very Good	Excellent
Process update	Weak	Fair	Good	Very Good	Excellent
Material update	Weak	Fair	Good	Very Good	Excellent
Finishing update	Weak	Fair	Good	Very Good	Excellent
Machine update	Weak	Fair	Good	Very Good	Excellent
DSS clarity	Weak	Fair	Good	Very Good	Excellent
DSS length	Weak	Fair	Good	Very Good	Excellent

Question 12:

Looking long term, do you think that the best form for this DSS is:

- a. A stand alone application
- b. Other (please state)
- c. A CAD Plug-in.
- d. Online application

Table 5-6: AMDSS First Version Questionnaire (Page 6 of 6).

5.1.2 *Questionnaire Observations and Analysis*

This section highlights the most important remarks of the users for the three parts of the questionnaire and discusses it.

1. **User Profile**

- Eleven out of thirteen users did not use any AM selectors which point that AM selectors in general are not very popular and users do not rely on them in practical.
- Users select AM processes, materials and finishing methods based on own experience, product needs, cost, lead time and service bureaus' recommendations.
- Users select AM machines based on build size, build time, availability, knowledge and service bureaus' recommendations.

2. **AMDSS Screens**

Process screen

Users had the following suggestions for improving the process screen:

- Sorting the fields of the screen in more logical order: length, width, height, quantity, accuracy, surface finish and minimum wall thickness instead of the current order which is: minimum wall thickness, accuracy, surface finish, quantity, length, width and height.
- Adding part volume.
- Adding delivery time.
- Adding platform shape.
- Adding overhung feature.
- Changing the wall thickness values to be thin < 2 mm, average from 2 mm to 6 mm and thick > 6 mm.
- Changing the surface finish terminology to be smooth, average and rough instead of excellent, good average and average.

Comments

- It is convenient to do the following changes to the process screen: sort the fields in more logical order, add part volume and change the surface finish terminology.
- Adding platform shape is of no value because AM can in principal address all shapes. The AM technologies can do any complex shapes which is the biggest advantage over the conventional manufacturing (Valentan et al.,2011).
- Adding overhung features is not a main concern because after discussing with experts and service bureaus all AM technologies can overcome this difficulty by a way or another. The idea that geometrical issue is less important is presented by Hague et al. (2004) where they stated that any complex shapes or features produced by CAD can be translated directly to the final part.
- Changing the wall thickness values as proposed from one of the users to be thin < 2 mm, average from 2 to 6 mm and thick > 6 mm is not helpful as the range used in the system is the most discriminatory for process choice.

Material Properties Screen

Users had the following suggestions for improving the material properties screen:

- Renaming sanitary conditions to medical consideration because sanitary condition term is not clear.
- Adding alternative units for material properties.
- Adding flexural modulus, biocompatibility, environmental impact, porosity and hygroscopic (ability of material to hold water) properties.

Users had the following preferences for the screening method:

- Choosing every time users make a selection between the general class screening and the properties screening.
- Having both minimum and maximum values when making selections.

- Making close matches materials appears on the possible material list so compromising can be done if the values of properties are near.

Comments

- Renaming sanitary conditions to medical consideration or bio-compatible was considered a good proposal.
- Having alternative units is not very useful because conversion can be done easily outside the AMDSS.
- Adding flexural modulus and environmental impact is not possible because of data unavailability.
- Adding porosity and hygroscopic was a good suggestion but not possible for all materials because of data unavailability.
- Both general class screening and the properties screening methods will be used.
- Using ranges (minimum and maximum) could overcome the problem of close matches material.
- Having both selections (selection based on minimum and selection based on maximum) would give a flexibility aspect to the AMDSS.

Criteria Weighting Screen

Users had the following suggestions for improving the criteria weighting screen:

- Adding build time.
- Adding impact strength and elongation.
- Adding cost or relative ranking of indicating cost (high, medium, low).

Comments

- Many users have seen the criteria presented sufficient.
- Adding elongation and or impact strength would not be possible because of data unavailability.

- Adding cost would be misleading to users because there is a difference between cost and price, so if a user takes a recommendation from the developed system and goes to a service bureau he will find different values.

Final Ranking Screen

Users had the following suggestions for improving the final ranking screen:

- Adding indicating cost.
- Adding information on material type such as resin, nylon.
- Some users did not want the score to be shown, while other wanted to see the breakdown of the score.

Comments

- Adding indicating cost was a good suggestion but could be misleading to users and giving inaccurate information.
- Adding information on material type or class was a good proposal.
- Showing the breakdown of the score was considered a good proposal.

For the process update screen and material update screen almost all the requirements of the users are the same like the process screen and material screen.

Machine Update Screen

Users had the following suggestions for improving the machine update screen:

- Adding beam diameter for laser machines because this is an indicator to accuracy.
- Adding machine availability.

Comments

- No need to add accuracy in machine because it was presented in the process screen.

- Machine availability differs from one place to another so it is difficult to be included in the system.

Finishing Update Screen

Users had the following suggestions for improving the finishing update screen:

- Adding the achieved finishing level from the finishing method.
- Adding finishing time of the finishing method.
- Adding information about the surface the finishing is applied to such as raw material or paint or lacquer and specifying surface reflectivity.

Comments

- Quantifying levels of finishing and knowing if the finishing method is applied to a raw metal or lacquer or paint were considered good suggestions.
- Adding finishing time is a good point but could be difficult because of the lack of information and also the variability from product to another.

3. AMDSS Screens

The general questions part of the questionnaire helped in understanding the weaknesses and strengths of the AMDSS. The following are some remarks and observation on the users' answers:

- Despite selecting process before material or material before process is the same because at the end users have to choose both, many users prefer to have the options to choose the order of the selection.
- The finishing options part was not helpful for many users and needed enhancement to give more information and assistance. Suggestions like: quantification and characterization, costing, ranking of the finishing methods, linking to applications and more process performance were all considered good suggestions that cannot be all done because of the data unavailability but still some improvement can occur.

- Advanced users did not see that the AMDSS helped them in the AM selection in general because they already know the answers. This is normal because they were not the target users for the system. The target users were the inexperienced and average users.
- One advanced user commented in the material selection that he has known a new material that he did not consider before. This shows that the available database could help advanced users to be updated with new materials instead of being stuck to the material they already know and frequently use.
- Majority of the users in the answer to the importance of system updating chose very important and extremely important. An updatable system without any programming required is one of the AMDSS strength points.
- Adding graphical examples and showing more help was considered an important point.
- Adding economic consideration was also a good suggestion. Although, it is difficult to develop a costing method that is realistic and could be applied correctly. There is a difference between price and cost.
- Users liked many things about the developed system such as: simplicity, easiness, range of materials, possibility of being updated and being a good source of information.
- Users did not like incapability of getting the close matches properties when selecting materials, lack of help information, different size of windows and screens, not having a good graphical interface, lack of guidance, having too many pop-up menus, changing the positions of back and next buttons and the lack of showing the breakdown of the final ranking score.
- Users were asked to rate the following elements: process selection, material selection, intermediate material selection, finishing selection, machine selection, process update, material update, finishing update, machine update, AMDSS clarity and AMDSS length with the following ratings: weak, fair, good, very good and excellent.

Many users rated from weak to fair the finishing selection, finishing update. The finishing selection is the weakest section in the AMDSS in providing helpful information.

- The choices of average and advanced users for the possible future of the AMDSS were as follows: the online application was chosen eight times, the CAD application was chosen six times, and the stand alone application was chosen twice.
- One user suggested that the update should not be the responsibility of the users. This remark needs to be underlined. Most of the users liked the update but they did not want to do it themselves. Some of them suggested having the possibility to download the updates over the internet from a trusted source.

5.2 User Testing and Evaluation

Four users have tangible products already manufactured and they have reached a decision on how to manufacture them. The four users used the AMDSS to get a recommendation and compared their selections to the system proposals. The aim of this process was to test the AMDSS by users already made a selection for their parts using their knowledge or by taking advice from experts.

5.2.1 Cover Part

Figure 5.1 shows the cover case study design. This case study was offered by RCID which is a multi-disciplinary engineering consultancy operating based in Newcastle University. Table 5-7 shows the part requirements and the material requirements for the part. The cover needed to be water resistant.

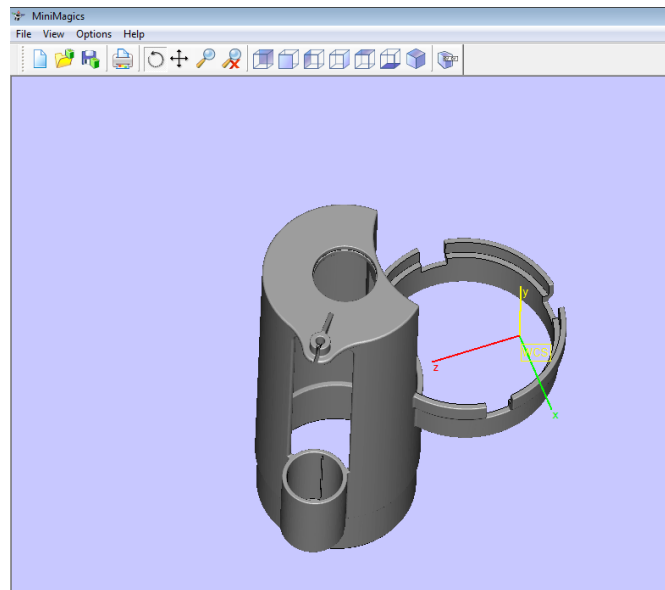


Figure 5.1: Cover Part

Part Requirements		Material Requirements	
Length (mm)	140	Water resistance	Yes
Width (mm)	87		
Height (mm)	177		
Minimum Wall Thickness (mm)	Average- Wide (>2 mm)		
Accuracy (mm)	Average (0.1-0.25 mm)		
Surface Finish Ra (μm)	Good-Average (0.32-12.5 μm)		
Quantity	1		

Table 5-7: Part and Material Requirements for the Cover Part

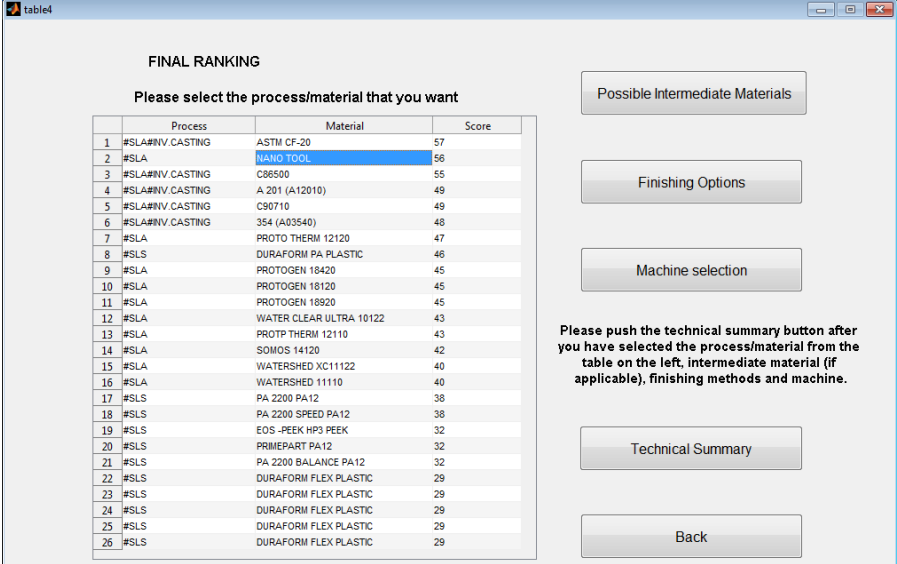
When the part information was fed to the AMDSS, the processes that the system offered were:

- EBM
- FDM
- Laser Cusing
- LENS
- SLA
- SLA + Investment Casting
- SLA + Silicone Tooling + Vacuum Casting

- SLS

When the material information was fed to the AMDSS, only the processes that have water resistant material are shown in the list. Figure 5.2 shows the final ranking screen for processes and the materials. The user selected the Nano tool material and the SLA process. For the finishing process, sand blasting was selected.

The outputs of the AMDSS conformed to the user selections for the process, material, finishing methods and machine. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 5.2 because there are other factors that affect the selections such as price given by service bureau and the availability of processes and materials. The Nano Tool material was proposed by the service bureau to the RCID although it is an expensive material. This ensures that recommendations of the service bureaus sometimes are for their interest and not for the interest of users. This case shows an example where the AM selectors would be very useful. User would have been able to go with the final ranking screen to the service bureaus and asks them about the cost of each alternative and then chose the optimum one instead of having the most expensive one.



FINAL RANKING

Please select the process/material that you want

	Process	Material	Score
1	#SLA#INV.CASTING	ASTM CF-20	57
2	#SLA	NANO TOOL	56
3	#SLA#INV.CASTING	C86500	55
4	#SLA#INV.CASTING	A 201 (A12010)	49
5	#SLA#INV.CASTING	C90710	49
6	#SLA#INV.CASTING	354 (A03540)	48
7	#SLA	PROTO THERM 12120	47
8	#SLS	DURAFORM PA PLASTIC	46
9	#SLA	PROTOGEN 18420	45
10	#SLA	PROTOGEN 18120	45
11	#SLA	PROTOGEN 18920	45
12	#SLA	WATER CLEAR ULTRA 10122	43
13	#SLA	PROTP THERM 12110	43
14	#SLA	SOMOS 14120	42
15	#SLA	WATERSHED XC11122	40
16	#SLA	WATERSHED 11110	40
17	#SLS	PA 2200 PA12	38
18	#SLS	PA 2200 SPEED PA12	38
19	#SLS	EOS -PEEK HP3 PEEK	32
20	#SLS	PRIMEPART PA12	32
21	#SLS	PA 2200 BALANCE PA12	32
22	#SLS	DURAFORM FLEX PLASTIC	29
23	#SLS	DURAFORM FLEX PLASTIC	29
24	#SLS	DURAFORM FLEX PLASTIC	29
25	#SLS	DURAFORM FLEX PLASTIC	29
26	#SLS	DURAFORM FLEX PLASTIC	29

Possible Intermediate Materials

Finishing Options

Machine selection

Please push the technical summary button after you have selected the process/material from the table on the left, intermediate material (if applicable), finishing methods and machine.

Technical Summary

Back

Figure 5.2: Final Ranking Screen of the Cover Part.

5.2.2 Drain Fitting Part

Figure 5.3 shows the drain fitting part design. Table 5-8 shows the part requirements and the material requirements for the part. This case study was offered by Keyworth Rapid Manufacturing Limited. The quantity required was 50 parts with a required strength of 50 MPa.

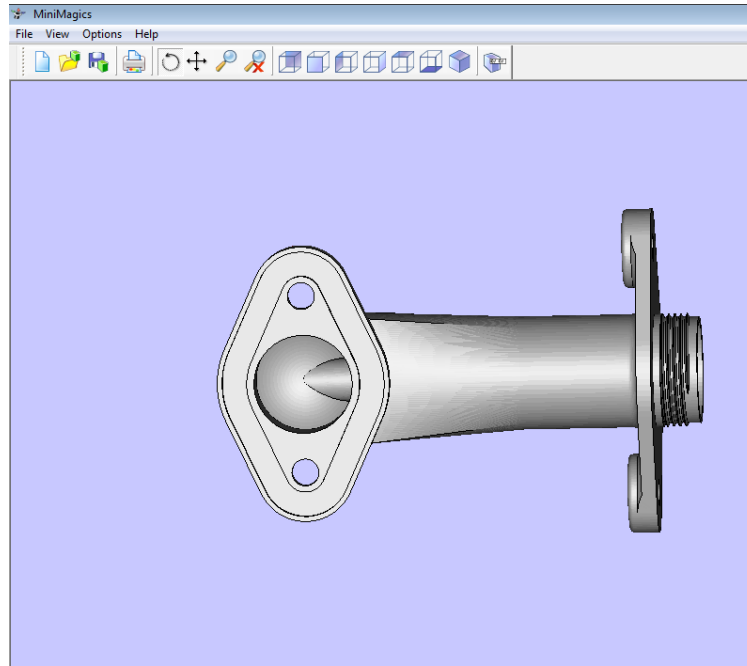


Figure 5.3: Drain Fitting Part.

Part Requirements		Material	
Length (mm)	97.5	Strength	50
Width (mm)	66		
Height (mm)	43.5		
Minimum Wall Thickness (mm)	Thin-Average (0.5 -2 mm)		
Accuracy (mm)	Average (0.1-0.25 mm)		
Surface Finish Ra (μm)	Good-Average (0.32-12.5 μm)		
Quantity	50		

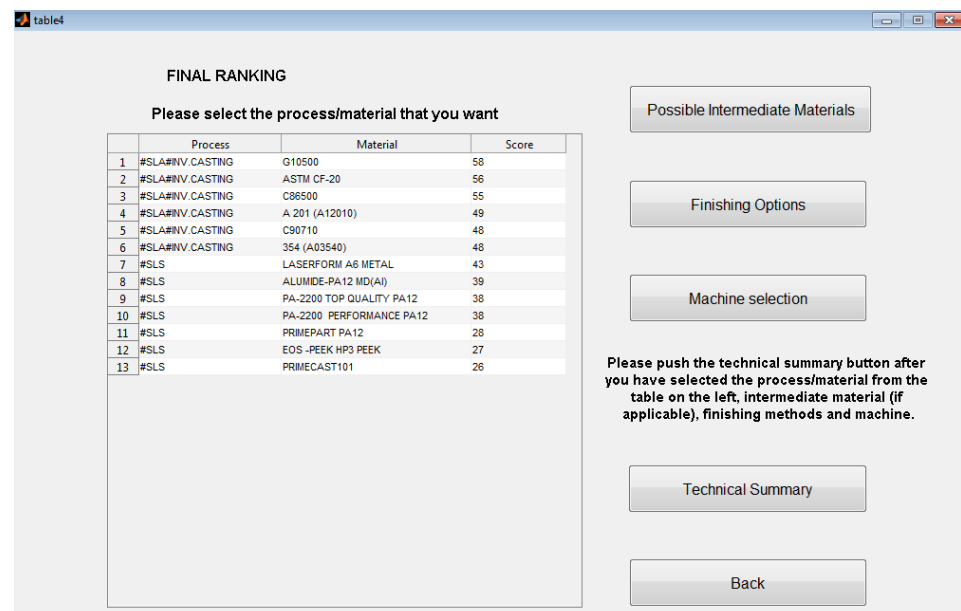
Table 5-8: Part and Material Requirements for the Drain Fitting Part.

When the part information was fed to the AMDSS, the processes that the system offered were:

- SLA + Investment Casting
- SLA + Reaction Injection Molding

- SLS

The user then input the material information. The output of the system was the final ranking screen which showed the processes and the materials which could manufacture the part as shown in Figure 5.4 The user selected the PA2200 PA12 material and the SLS process. For the finishing process, sand blasting was selected. The outputs of the AMDSS conformed to the user selections for the process, material, finishing method and machine. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 5.2 because there are other factors that affect the selections such as price given by service bureau and the availability of processes and materials. The price was the main factor that made the user chose the PA2200 PA12 and also the availability of an SLS process in-house.



FINAL RANKING

Please select the process/material that you want

	Process	Material	Score
1	#SLA#INV.CASTING	G10500	58
2	#SLA#INV.CASTING	ASTM CF-20	56
3	#SLA#INV.CASTING	C86500	55
4	#SLA#INV.CASTING	A 201 (A12010)	49
5	#SLA#INV.CASTING	C90710	48
6	#SLA#INV.CASTING	354 (A03540)	48
7	#SLS	LASERFORM A6 METAL	43
8	#SLS	ALUMIDE-PA12 MD(AI)	39
9	#SLS	PA-2200 TOP QUALITY PA12	38
10	#SLS	PA-2200 PERFORMANCE PA12	38
11	#SLS	PRIMEPART PA12	28
12	#SLS	EOS -PEEK HP3 PEEK	27
13	#SLS	PRIMECAST101	26

Possible Intermediate Materials

Finishing Options

Machine selection

Please push the technical summary button after you have selected the process/material from the table on the left, intermediate material (if applicable), finishing methods and machine.

Technical Summary

Back

Figure 5.4: Final Ranking Screen for The Drain Fitting Case Study

5.2.3 Filter Cover Part

Figure 5.5 shows the filter cover case study design. This case study was offered by Paragon Rapid Technologies Limited a rapid prototyping service bureau. Table 5-9 shows the part requirements and the material requirements of the part. The material requirements were: black colour, a heat deflection temperature of 110 °C, a hardness (shore D) of 90, and a need to be water resistant.

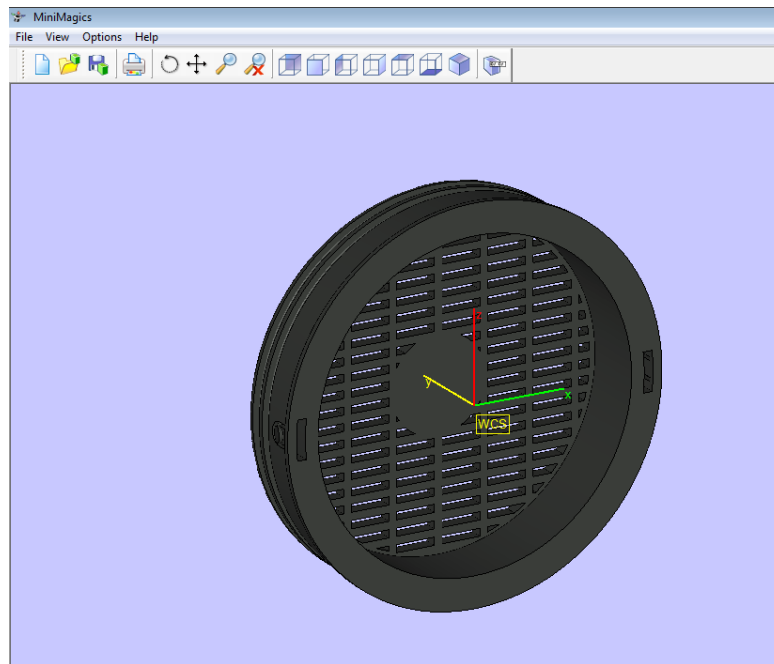


Figure 5.5: Filter Cover Part.

Part Requirements		Material Requirements	
Length (mm)	148	HDT (°C)	110
Width (mm)	30	Colour	Black
Height (mm)	148	Hardness (shore D)	90
Minimum Wall Thickness (mm)	Thin-Average (0.5 -2 mm)	Water Resistance	Yes
Accuracy (mm)	Average (0.1-0.25 mm)		
Surface Finish Ra (µm)	Good-Average (4 µm)		
Quantity	1		

Table 5-9: Part and Material Requirements for the Filter Cover Part.

When the part information was fed in the AMDSS, the processes selected were:

- EBM
- Laser Cusing
- LENS
- SLA
- SLA + Investment Casting
- SLA + Reaction Injection Molding
- SLS

When the material information was fed to the system, Figure 5.6 appeared and showed that there was conflict between colour and hardness. There was no black material that also had hardness shore (D) equal to 90. Because many materials could be pigmented at the end of the process, the user decided to relax this constraint. The back button was pressed and the black colour was removed.

	Strength	Tensile	Hardness	HDT	Color	Density	Dielectric strength	Sanitary	Water resist	Heat resist
Strength		Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected
Tensile	Not selected		Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected
Hardness	Not selected	Not selected		Ok	prb	Not selected	Not selected	Not selected	Ok	Not selected
HDT	Not selected	Not selected	Ok		Ok	Not selected	Not selected	Not selected	Ok	Not selected
Color	Not selected	Not selected	prb	Ok		Not selected	Not selected	Not selected	Ok	Not selected
Density	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected	Not selected
Dielectric strength	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected	Not selected
Sanitary	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected		Not selected	Not selected
Water resist	Not selected	Not selected	Ok	Ok	Ok	Not selected	Not selected	Not selected		Not selected
Heat resist	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	Not selected	

Back

Figure 5.6: Screen that Shows the Material Parameters in Conflict Together.

Figure 5.7 shows the possible processes and materials found by the system after removing the black colour requirement. The only process was SLA and the only material was a material called Nano Tool. Although, the user of this case study was an expert user he did not know about this material before. This underlines that sometimes the AMDSS system could be beneficial to the expert users not from the point view of the logic of selection but from the point of view of providing new updated information.

The real selection of the process and the material for this part was SLS process and nylon 12 (PA2200 PA 12) and then pigmented to black color. Looking at the material data sheet of the PA2200 PA12 material, a remark was made that the hardness is 75 shore D and not 90. The expert user when making the actual selection had compromised on hardness. So the back button was pressed and the hardness requirement was relaxed from 90 to 75.

	MATERIAL ...	PROCESS	MATERIAL	STRENGTH	MODULUS	HARDNESS	DENSITY	DIELECTRIC STRENGTH	HDT
1	2 #SLA		NANO TOOL	78	11400	94	2	3	225

Figure 5.7: Possible Process and Material that Can Manufacture the Filter Cover Part after Removing the Black Color Requirement

	MATERIAL ...	PROCESS	MATERIAL	STRENGTH	MODULUS	HARDNESS	DENSITY	DIELECTRIC STRENGTH	HDT
1	2 #SLA		NANO TOOL	78	11400	94	2	3	225
2	4 #SLA		PROTO THERM 12120	77	3250	87	1	3	146
3	89 #SLS		PA 2200 PA12	47	1650	75	0.9300	0	150
4	91 #SLS		PA 2200 SPEED PA12	42	1650	75	0.9300	0	150

Figure 5.8: Possible Process and Material that Can Manufacture the Filter Cover Part after Relaxing Hardness Requirement.

When the hardness was changed to 75, the SLS process and the PA2200 PA12 appeared in the list. The user commented that adding a range of minimum and maximum values would help. So in this case instead of having one value which was the 90, it could be a range of values between 75 and 90.

Finally, the user selected sanding as the finishing process and chose the EOS P730 machine for part manufacturing.

After exploring the decision making process, the outputs of the AMDSS conformed to the user selections for the process, material, finishing method and machine. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 5.8 because there are other factors that affect the selections such as cost of the service bureau and the availability of processes and materials. In addition, the color of material is not very important in most of the cases because many materials could be pigmented easily within a surface finish process.

5.2.4 *Dental Implant Part Assembly*

Figure 5.9 shows the dental implant part design. This part was one of several parts assembled together. This case study was offered by one of the research candidate at Newcastle University named Mr. Shah Fenner Khan. Table 5-10 shows the part requirements and the material requirements for the part. The required heat deflection temperature was 90 °C.

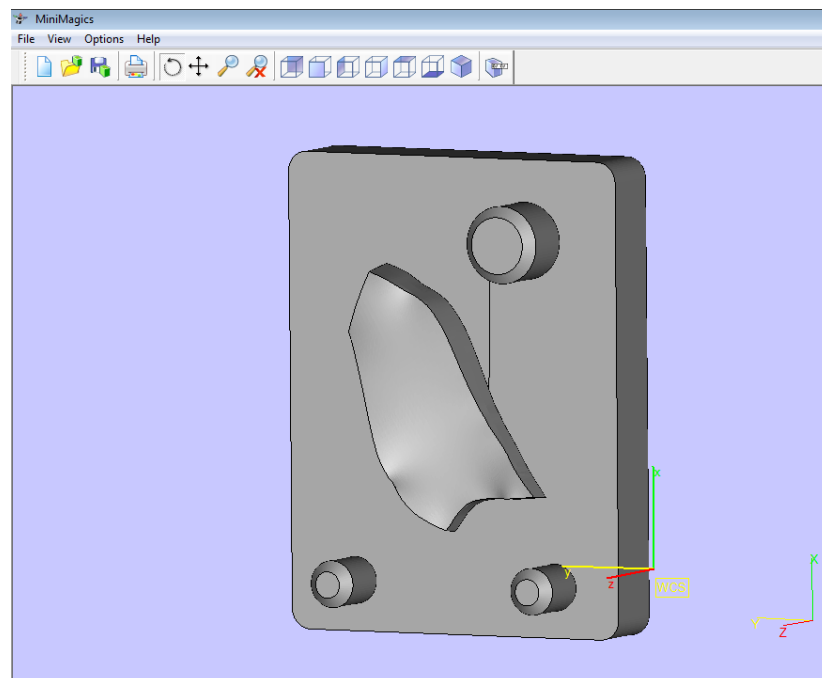


Figure 5.9: Dental Implant Assembly Part.

Part Requirements		Material Requirements	
Length (mm)	36	HDT (°C)	90
Width (mm)	47		
Height (mm)	10		
Minimum Wall Thickness (mm)	Thin -Average(0.5-2.00 mm)		
Accuracy (mm)	Tight <0.1 mm		
Surface Finish Ra	Average Rough(>12.5 µm)		
Quantity	1		

Table 5-10: Part and Material Requirements for the Dental Implant Assembly Part.

When the part information was fed to the AMDSS, the processes for this part were as follows:

- EBM
- Laser Cusing
- LENS
- SLA
- SLA + Investment Casting
- SLA + Reaction Injection Molding

When the material information was fed to the AMDSS, only SLA was recommended because only some of the SLA materials could achieve the heat deflection temperature (HDT) of 90 °C. The user of this case study gave the HDT criterion weight of 10 and left the rest criteria empty. Figure 5.10 shows the final ranking screen which showed the ranked processes and the materials that can manufacture the part. The user selected the Protogen 18920 material and the SLA process. For the finishing process, polishing was selected and finally for the machine Viper SLA was selected. The outputs of the AMDSS conformed to the user selections for the processes, materials, finishing methods and machine. It has to be underlined that the selections of process and material made by the user were not the first ranked as shown in Figure 5.10 because there are other factors that affect the selections such as price given by service bureau and the availability of processes and materials. The price was the main factor here.

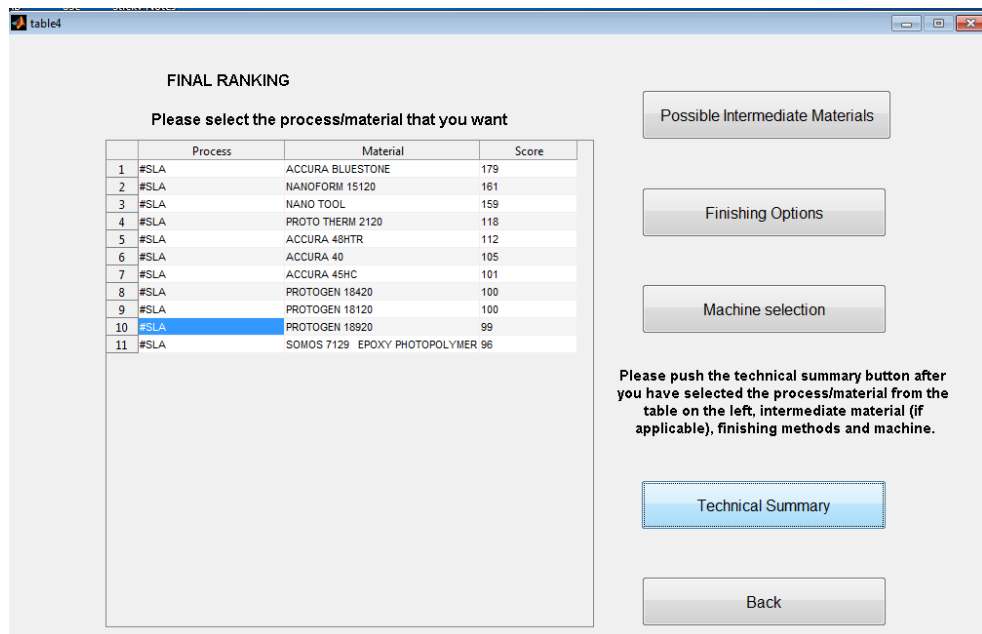


Figure 5.10: Final Ranking Screen of the Dental Implant Part.

Comments

- The responses of the users to the questionnaire and the AMDSS testing with the four given parts showed that there is a need for further development and more work is needed so the developed system could present what customers and users need. Chapter 6 describes how the AMDSS was further developed.
- The testing of the AMDSS with the given four parts showed that the AM selector could be useful for the inexperienced and average users because it shows them all possible AM manufacturing routes for their parts regarding process chains, materials and finishing options which saves them time and cost and provides them with the information needed before going to service bureaus to manufacture a part.

Chapter 6. Additive Manufacturing Decision Support System Further Development and Assessment

This chapter describes the seventh and eighth steps respectively in the AMDSS design: further development made to the AMDSS and obtaining further feedback from users for assessment purpose. The feedback was gathered through making a second questionnaire which was a modified version of the first questionnaire. A total of six persons responded to the questionnaire. Three of them were advanced users and the other three were average users. Two of the six users have responded previously to the first questionnaire and the other four were new users and have not tested the system before.

6.1 AMDSS Second Version

6.1.1 *List of Modifications*

The following are the modifications that were made to the first version of the AMDSS based on the inputs of the users:

1. Option of selecting process first or material first.
2. Option of selecting material by class (polymers, metals and ceramics).
3. Volume calculations are shown when users enter the length, width and height of the part.
4. Rearranging the order of the inputs of the process selection screen to be length, width, height, quantity, accuracy, surface finish and minimum wall thickness.
5. Renaming the surface finish ranges to be: smooth, average and rough.
6. Adding the maximum values to some of the inputs of the materials properties screen (strength, modulus, hardness shore D and heat deflection temperature).
7. Adding new inputs to the material properties screen like: hardness Vickers and melting point. Both new inputs have minimum and maximum ranges.
8. Renaming sanitary conditions to bio-compatible in the material properties screen.

9. Changing the sequence of the windows starting from the final ranking screen to be in the following order: 1- selecting intermediate material, 2- selecting finishing methods, 3- selecting machines and 4- previewing the technical summary. There is a possibility that users can skip any step and go to the technical summary directly.
10. Improving the finishing selection by:
 - i. Changing the finishing to be finishing methods path instead of single finishing method.
 - ii. Adding the surface finish level (Ra) that can be achieved by the selected path.
 - iii. Adding finishing advice that could be updated.
11. Changing the updating panels to match the modifications made to the new improved version of the AMDSS.
12. Adding help files in some screens to guide users and give them appropriate information.
13. In ranking the alternatives with SMART method there is a possibility to revert the direction of sorting for some criteria such as density, hardness and dielectric strength. These criteria could to be ranked considering that minimum values are better or considering that maximum values are better (which is the default) because some users would request that lower density and/or lower hardness and/or lower dielectric strength would be better for their designs.

6.1.2 *Graphical User Interface Modifications*

Some screens were changed and some screens were added based on the modifications made. The first change made was to the first screen that appears when users start the system. Figure 6.1 shows the revised start screen. There are two options in the selection panel in the second version: 1- select process first and 2- select material first. In the first version, the start screen had only one button called selection module and this was selecting process first.

The other screens that had been changed were described in the next section to better understand the KBS modifications and the relationships between the KBS and the GUI within the developed AMDSS.



Figure 6.1: Start Screen of the Second Version of the AMDSS

6.1.3 Knowledge Based System Modifications

The KBS consists of three parts which are: 1- selection, 2- browse and 3- update. The modifications were made to the selection part. Consequently, the update part needs to be changed to cope with the changes made in the selection part. No changes have been made to the browse part. The following sections discuss: 1- the selection part modifications and 2- the update part modifications.

1. Selection Part Modifications

IDEF0 model development for the selection part of the AMDSS second version

An IDEF0 model was developed to describe the selection part of the second version of the AMDSS, which was a modified version of the first version. Figure

6.2 shows the IDEF0 tree of the second version and Table 6-1 shows the IDEF0 node index. In the IDEF0 diagrams the modified and new activities have been shaded to show the changes were made.

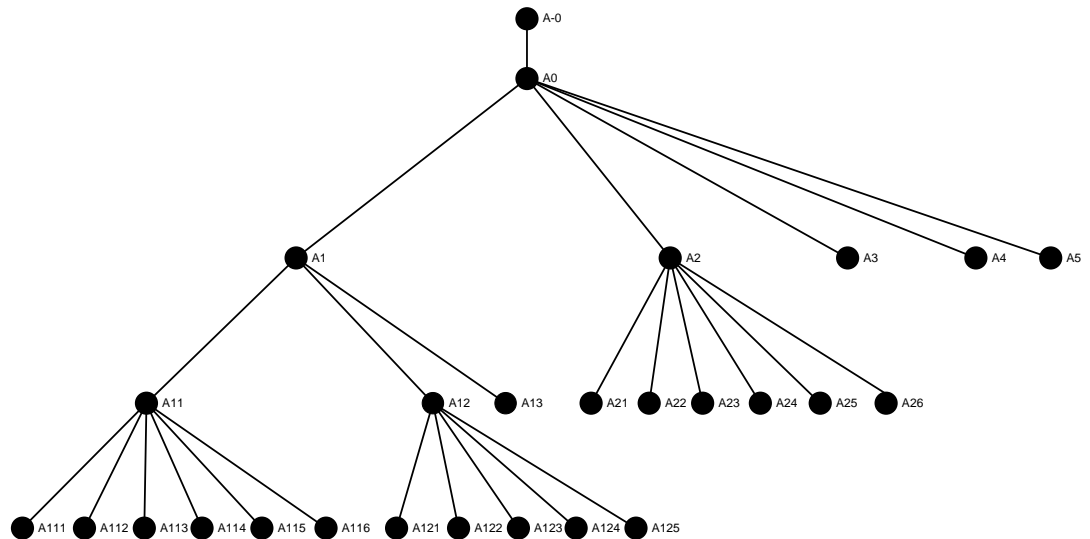


Figure 6.2: IDEF0 Node Tree Diagram for the Second Version of the AMDSS

One important piece of information about the IDEF0 is that the activities in the rectangular boxes do not have to be in sequence. When a person develops an IDEF0 model the two options are available: building the boxes in sequence or building the boxes without sequence (IDEF,2012). The need for building boxes without sequence appeared in the second version of the AMDSS model in A0 diagram.

The sequence of the selection of AM processes and materials in the second version could be made via four paths and not in only one path selection as for the first version. The use of the block diagram to illustrate the new different selection paths was essential to avoid repeatability in the IDEF0 model. Figure 6.3 shows a block diagram of one path selection of the first version. Users made the selections in the following order: process, material by properties, ranking, intermediate materials, finishing methods and machines.

A0 Develop an Additive Manufacturing Decision Support System (AMDSS)

A-0 Main Steps of the Selection Part of the KBS

A1 Check AM possible processes and Material

A11 Check AM possible process

A111 Connect to the database and get the processes that satisfy minimum wall thickness.

A112 Connect to the database and get the processes that satisfy minimum accuracy.

A113 Connect to the database and get the processes that satisfy minimum quantity.

A114 Connect to the database and get the processes that satisfy minimum surface finish.

A115 Connect to the database and get the processes that satisfy the required volume.

A116 Intersect all process lists.

A12 Check AM possible materials by properties

A121 Connect to the database and get all the material that satisfy the general properties.

A122 Connect to the database and get all the material that satisfy the mechanical properties.

A123 Connect to the database and get all the material that satisfy the electrical properties.

A124 Connect to the database and get all the material that satisfy the thermal properties.

A125 Connect to the database and get all the material that satisfy the environmental properties.

A126 intersect all material lists.

A13 Check AM possible materials by class

A2 Rank using SMART method

A21 Enter the weights of each criterion from 1 to 10.

A22 Normalize the weights.

A23 Divide each alternative score value by the maximum alternative score value for each criterion and multiply by 10.

A24 Revert the direction of ranking for some criteria if needed.

A25 Multiply normalized score values by the normalized weights.

A26 Sum the weighted score values for each alternative and sort.

A3 Check possible machines

A4 Check possible finishing methods

A5 Check possible intermediate materials

Table 6-1: IDEF0 Node Index (version2).

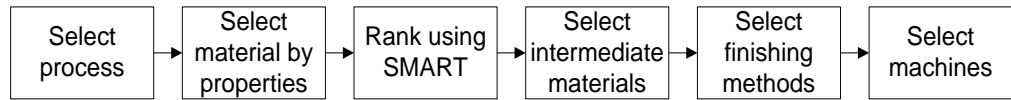


Figure 6.3: Selection Path of the First Version of the AMDSS

Figure 6.4 shows the block diagram of the new four paths. Users can select 1- process then material by properties, 2- select process then material by class, 3- select material by properties then select process and 4- select material by class then select process. For all the four paths the rest of the path order are the same: ranking, select intermediate materials, select finishing methods and select machines.

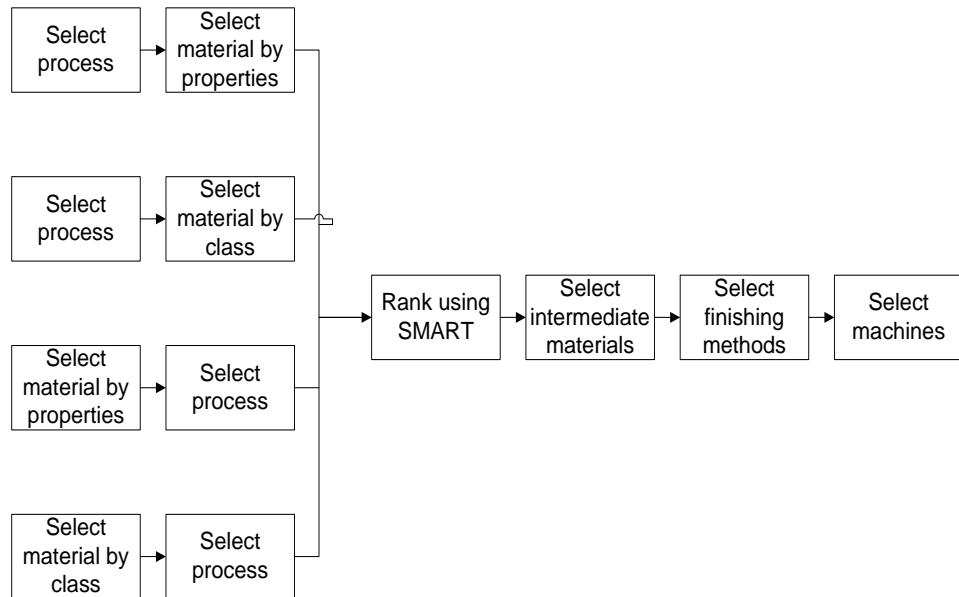


Figure 6.4: Selection Paths of the Second Version of the AMDSS

Figure 6.5 shows the node A-0 of the second version which is the same as the first version A-0 node. Figure 6.6 shows the A0 diagram which explains the revised main steps of the selection part of the KBS. Figure 6.7 shows the A1 diagram which is: check the AM possible processes and materials. Figure 6.8 shows the A11 diagram which is: Check AM possible processes. The only change is in activity five. The KBS checks the volume of the processes and not each dimension by itself like in the first version. Figure 6.9 represents the A12 diagram which is: Check AM material by properties.

The modifications to the A12 diagram were: 1- New inputs added to the mechanical properties box such as: maximum hardness (shore D), minimum hardness Vickers, maximum hardness Vickers, maximum modulus and maximum strength. 2- New inputs added to the thermal properties such as: maximum heat deflection temperature, minimum melting point and maximum melting point. 3- Replacing the sanitary conditions with the bio-compatible condition.

Figure 6.10 shows the A2 diagram: Rank using SMART method. No changes were made to this diagram.

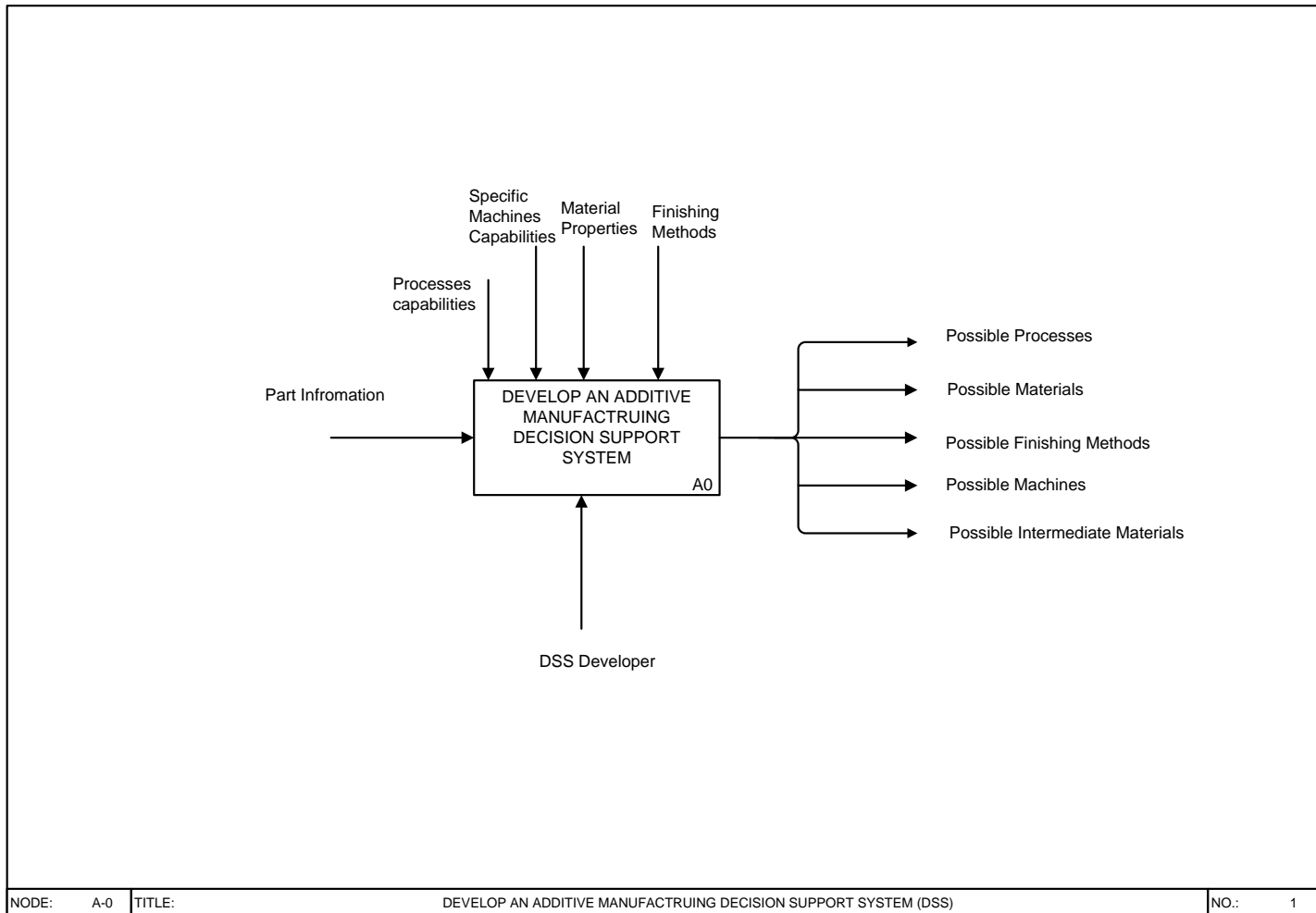


Figure 6.5: A-0, Develop an Additive Manufacturing Decision Support System (Version2)

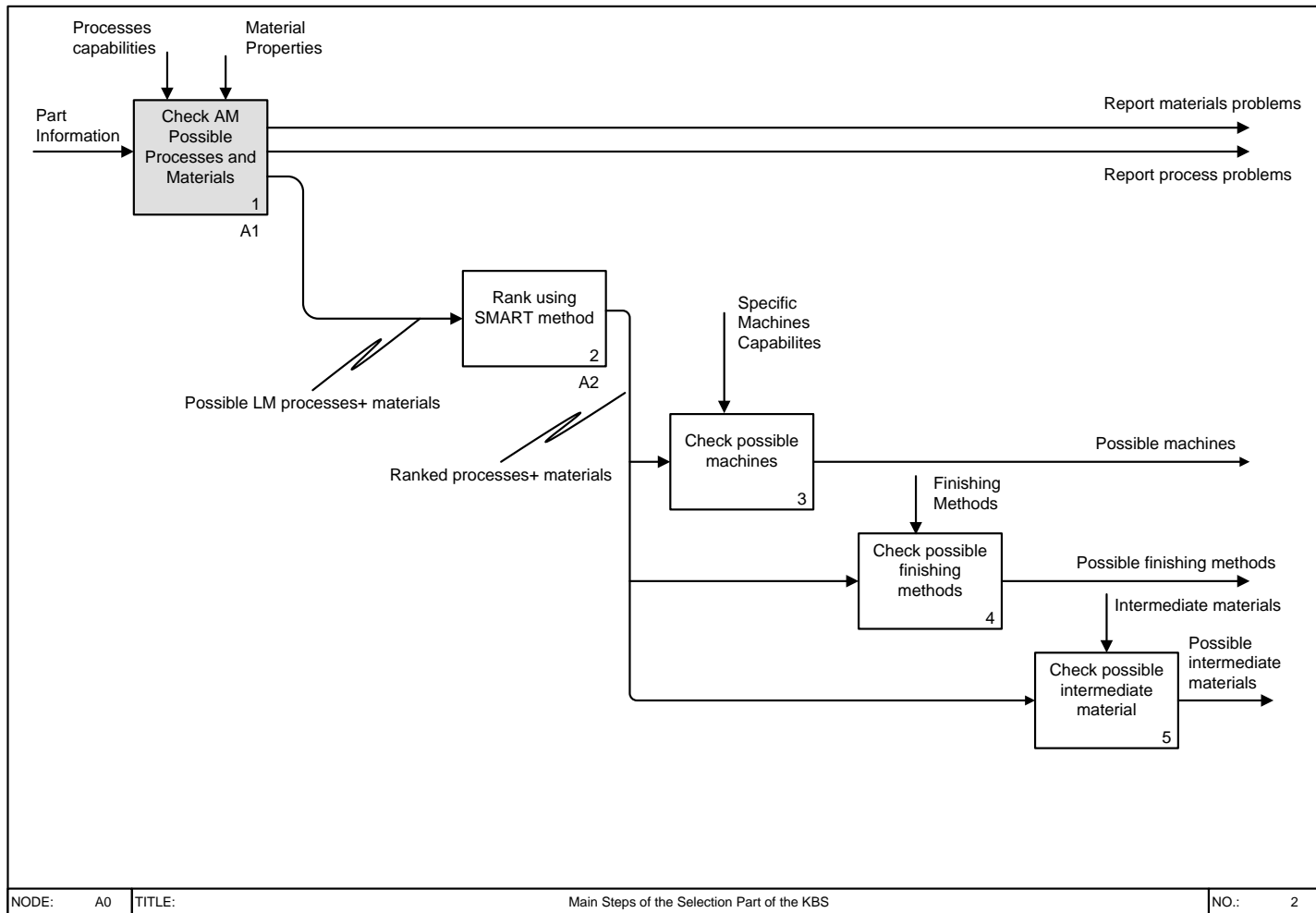


Figure 6.6: A0, Main Steps of the Selection Part of the KBS (Version 2).

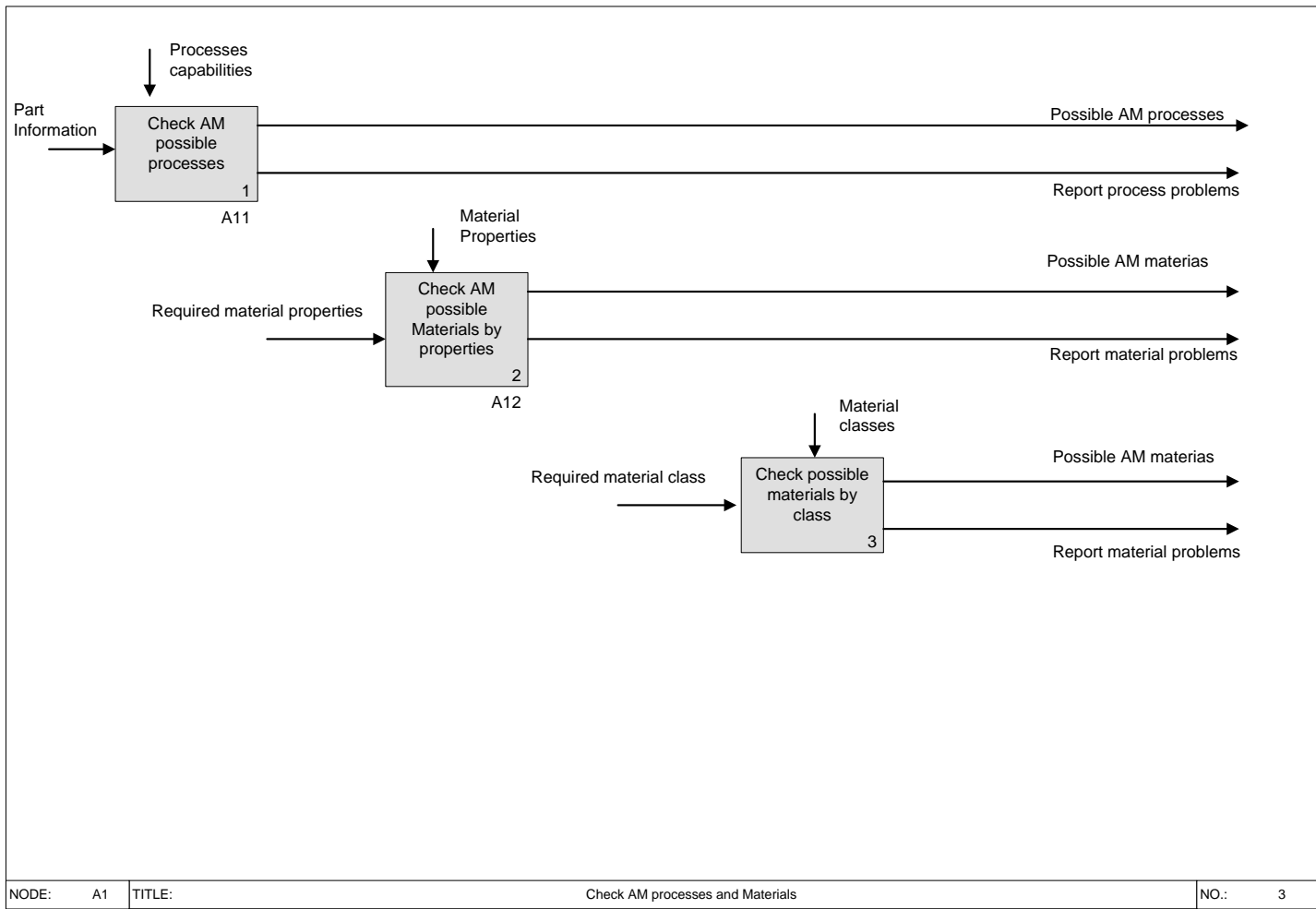


Figure 6.7: A1, Check AM Processes and Materials (Version 2).

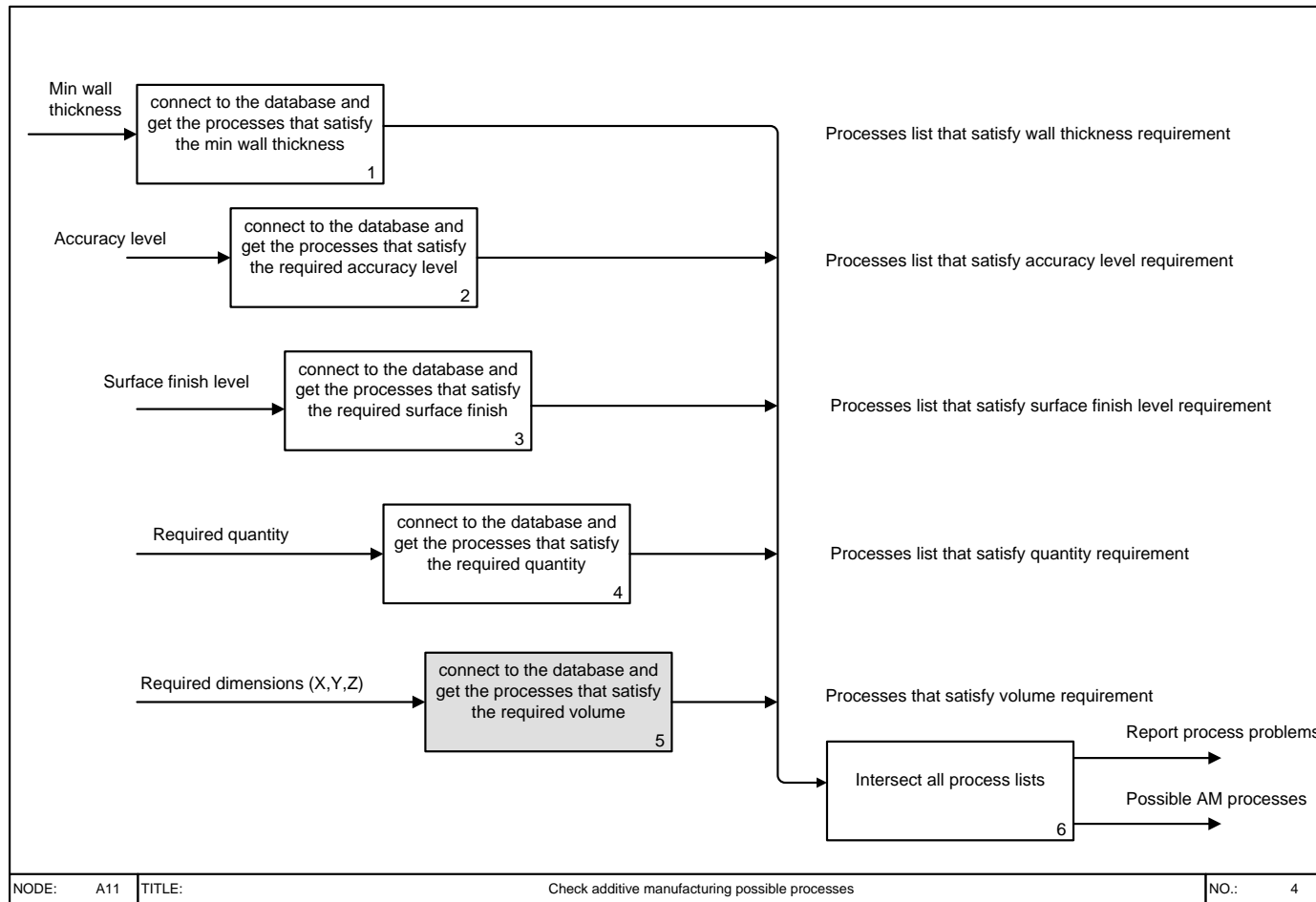


Figure 6.8: A11, Check AM Processes (Version 2).

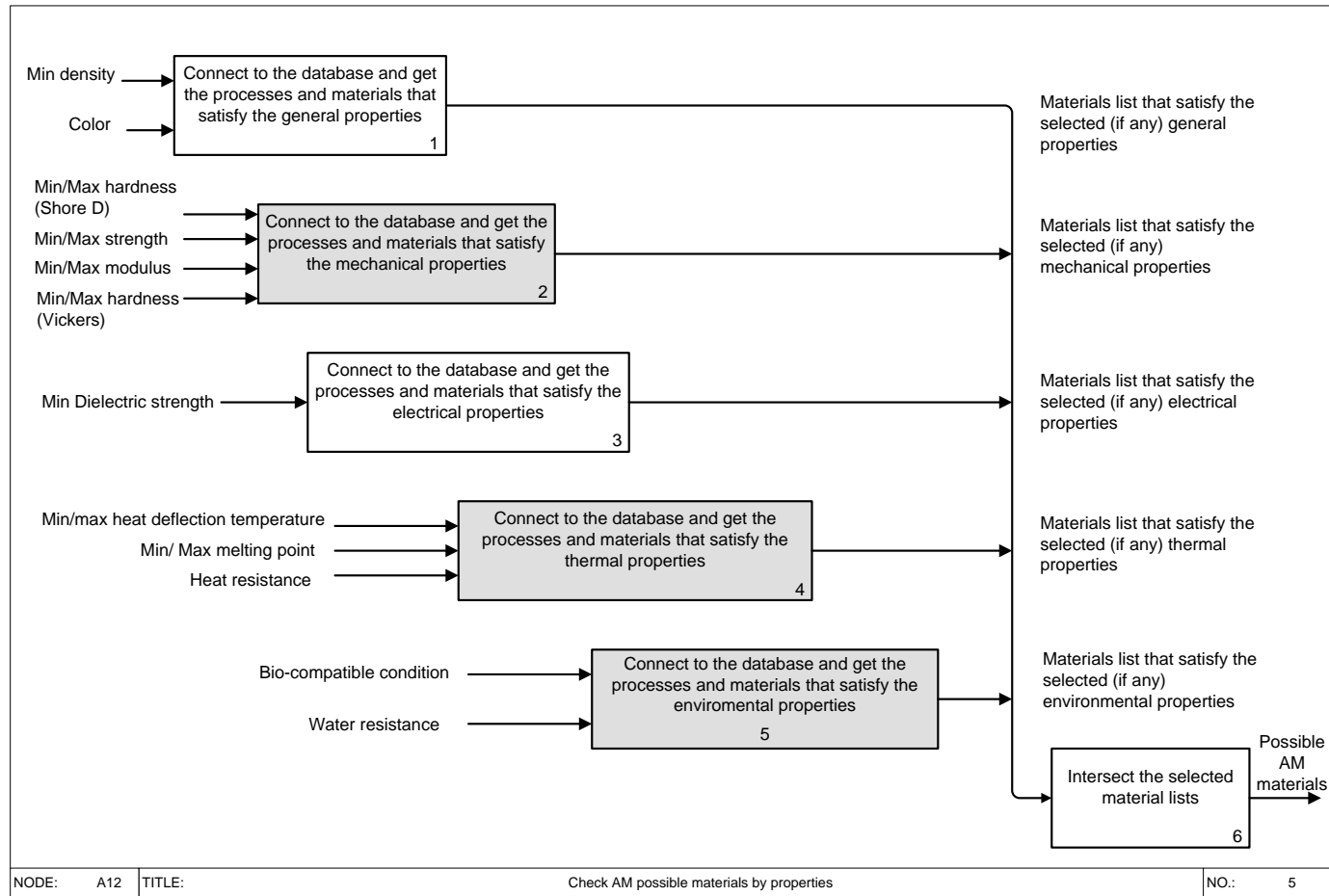


Figure 6.9: A12, Check AM Materials by Properties (Version 2).

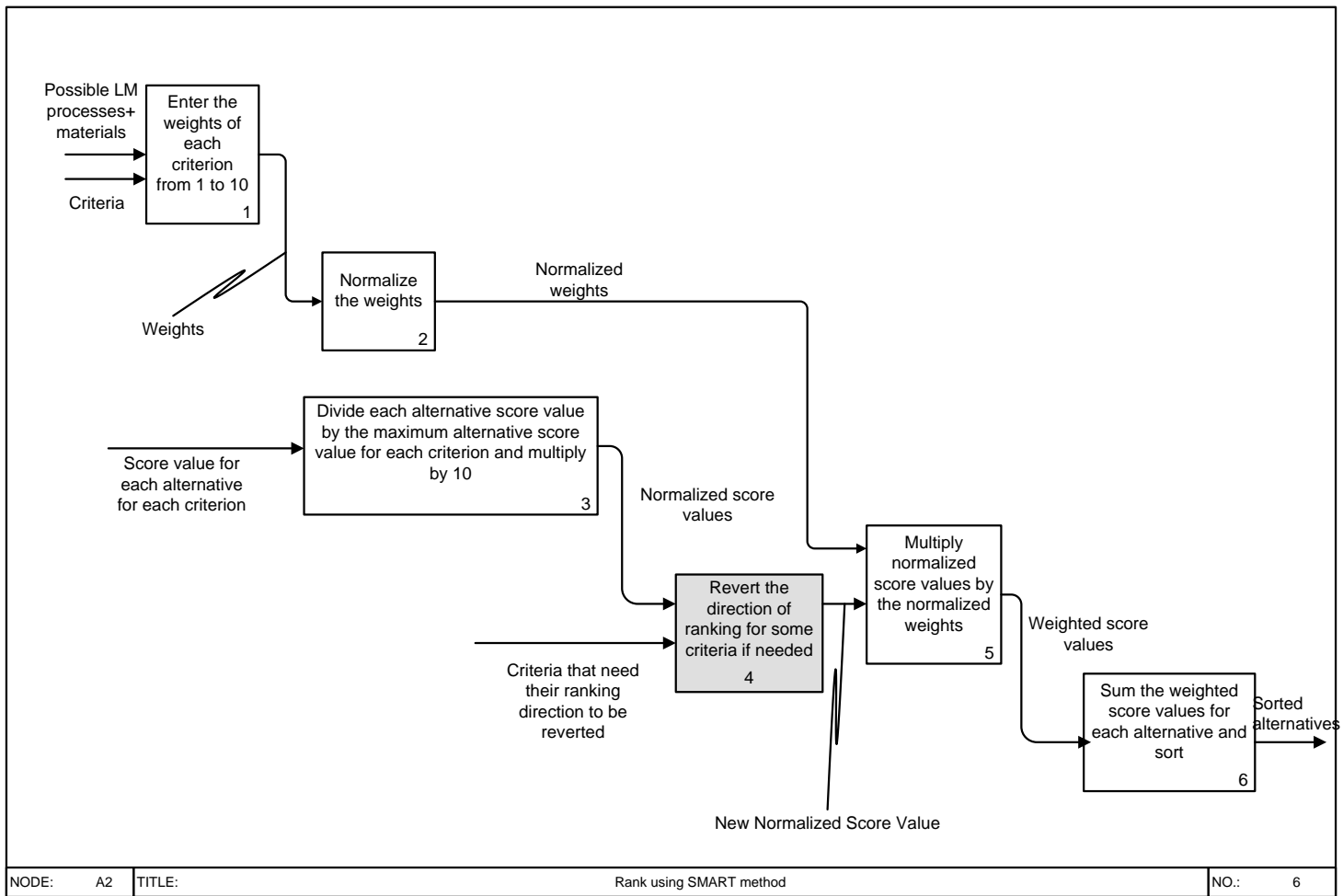


Figure 6.10: A2, Rank Using SMART Method (Version 2).

Modifications to the elements of the selection part of the KBS

The selection part of the KBS consists of six elements as described before in chapter 3 which are: the process chain selection element, the material selection element, the ranking element, the finishing options element, the intermediate material selection element and the machine options element. The modifications were done to only four elements: the process chain selection element, the material selection element, the ranking element and the finishing options element.

I. Process Chain Selection Element

The screenshot shows a software window titled 'process2' with a 'PROCESS SELECTION' interface. A central panel prompts the user to 'PLEASE SELECT ALL FIELDS'. The panel contains seven input fields: LENGTH (mm) set to 200, WIDTH (mm) set to 100, HEIGHT (mm) set to 300, QUANTITY (dropdown menu), ACCURACY (dropdown menu), SURFACE FINISH (dropdown menu set to SMOOTH(0-0.32µm)), and MIN WALL THICKNESS (dropdown menu). Below the panel, the VOLUME (mm3) is shown as 6e+006. At the bottom, there are three buttons: 'RESET ALL VALUES', 'Back', and 'FIND SUITABLE PROCESSES'.

Figure 6.11: Process Selection Screen of AMDSS (Version 2).

Figure 6.11 shows the process selection screen of the second version where users enter the values of the process input variables. Based on feedback of the users the order of the input variables have been changed to be length, width, height, quantity, accuracy, surface finish and minimum wall thickness instead of minimum wall thickness, accuracy, surface finish, quantity, length, width and height in the first version. In addition, the terminology of the surface finish ranges were changed to be smooth (0 - 0.32 µm), average (0.32-12.5 µm) and rough

(>12.5 μm). The terminologies in the first version were excellent (0 - 0.32 μm), good-average (0.32-12.5 μm) and average rough (>12.5 μm).

The volume calculation is added to the screen. When users enter values of X, Y and Z, the volume is calculated automatically and appears on the screen. Furthermore, the selection of the possible processes in the first version was based on comparing the X, Y and Z fed to the system by user and comparing them to the maximum X, Y and Z available in the database (parameter by parameter). This logic has been changed in the second version. The selection is based on a comparison between the required volume and the available volume. The processes that are not satisfying the volume requirement are excluded from the possible processes list.

There are two issues regarding the volume calculations that have to be mentioned: First, the orientation of the part was not taken into consideration. This means that sometimes the part will fit in a specific volume but this is not the optimum build scenario for it. The reason of this issue is that the process planning was not included in the system and is beyond the scope of this research. Secondly, the filtering of the possible processes using volume can fail in some circumstances. For example, in an extreme conditions such as the a process that has very small dimensions table X, Y and very high Z the volume calculation would tell the user that the process could meet his requirements but in reality the X and Y of the part cannot be laid down on the process table because the X and Y of the part are bigger than X and Y of the table.

Process selection logic flowchart

Figure 6.12 shows a flowchart that describes the steps of the process selection. A modification was done that the KBS deals with the calculated volume. The shaded part in the flowchart shows the new steps: get from the database all the processes, calculate the volume of each process and get a list of the processes to which their volume is bigger than or equal to the required volume.

A decision then has to be made: if the processes list is empty then add to the reasons list that there is no process in the database can meet the required volume and continue to the next step but if the processes list is not empty then the KBS

continues the next step directly which is intersecting all the process lists to get a process list that satisfies all process variables.

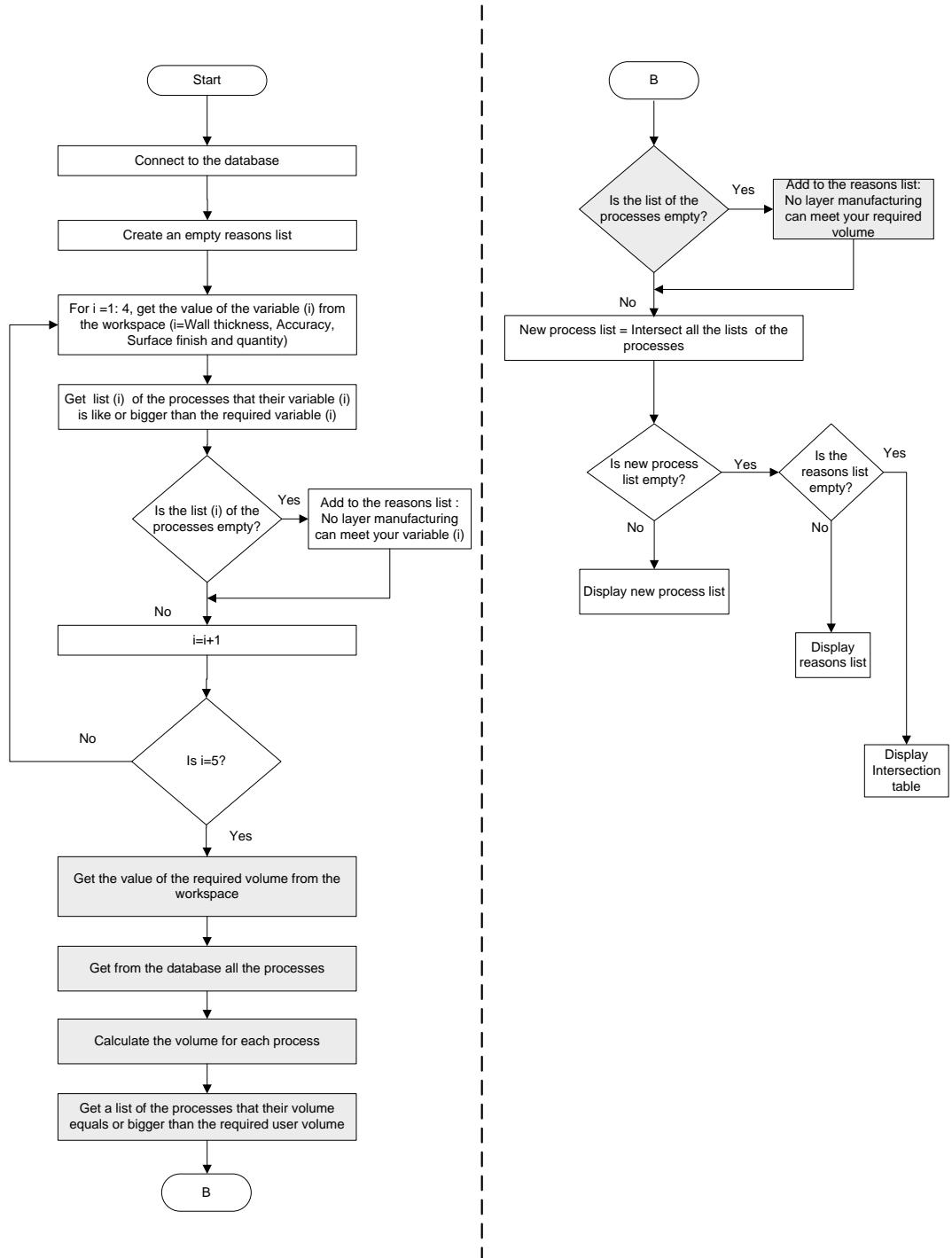


Figure 6.12: Checking AM Processes Flowchart of the AMDSS (Version 2).

II. Material Selection Element:

The second version of the material selection element has two options for the material selection as shown in Figure 6.13: 1- selecting material by properties, when selected a new window is opened shown in Figure 6.14 and 2- selecting material by class such as polymers, metals and ceramics, when selected a new window is opened shown in Figure 6.15.

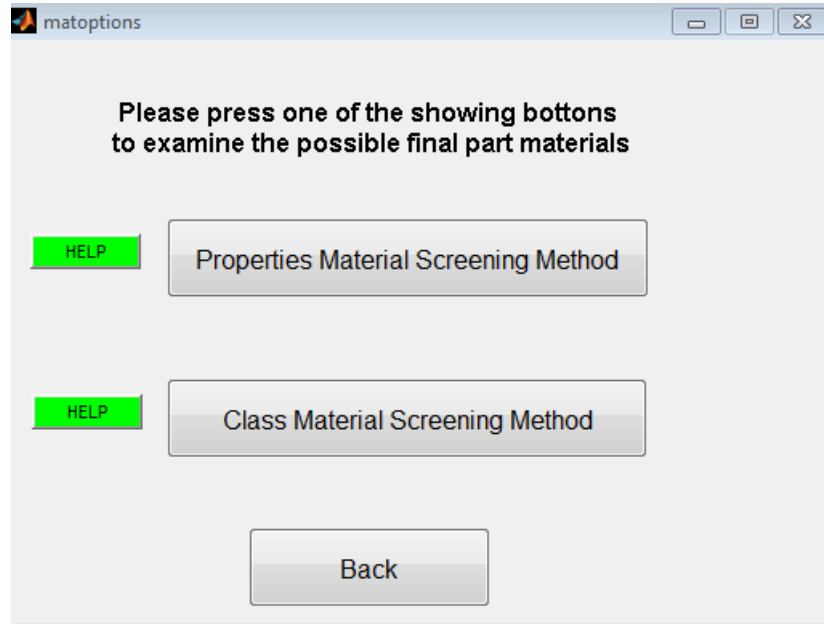


Figure 6.13: Choosing Material Screening Method of the AMDSS (Version2).

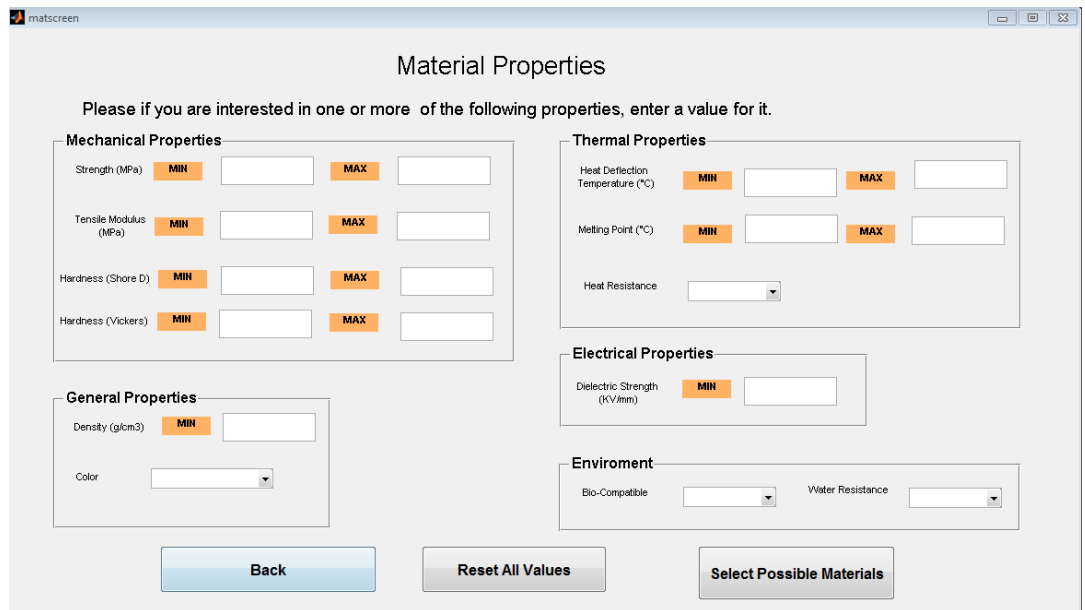


Figure 6.14: Material Properties Screen of the AMDSS (Version 2).

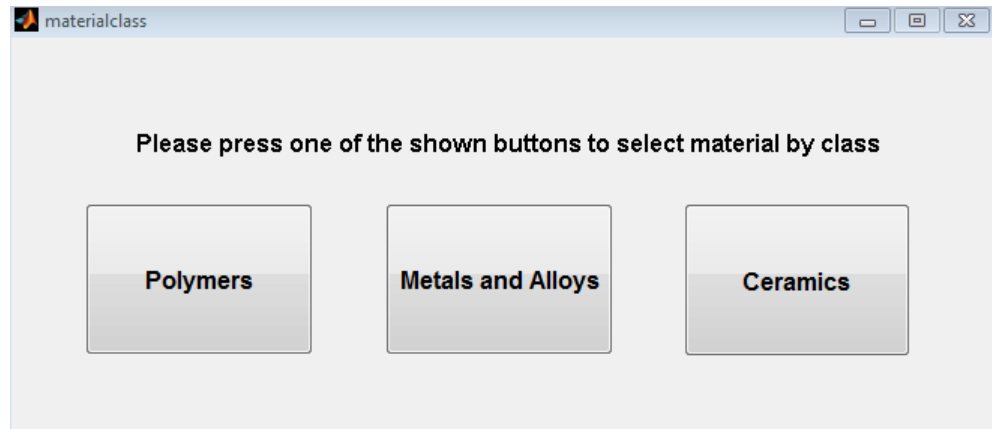


Figure 6.15: Material Class Screen of the AMDSS (Version 2).

Selecting material by properties

In the second version, new inputs were added to the material input screen. These inputs were: 1- maximum strength, 2- maximum tensile modulus, 3- maximum hardness (Shore D), 4- minimum hardness (Vickers), 5- maximum hardness (Vickers), 6-maximum heat deflection temperature, 7- minimum melting point, 8- maximum melting point. The idea of adding the maximum ranges of some variables is that some users or designers would like to have a range instead of just having a minimum value. In addition some users would use the maximum only. For the hardness, users could select only one type of hardness either shore D or hardness Vickers, they cannot choose both.

Selecting material logic flowcharts

Figure 6.16 and Figure 6.17 show flowcharts of the assessment of AM materials by the second version of the AMDSS. The flowcharts are modified flowcharts of the first version. The modifications are shaded to allow them to be distinguished.

The KBS obtains the material variables from the workspace. The material variables are divided into four groups.

The first group is (minimum values group). It includes six variables which are: minimum density, minimum strength, minimum modulus, minimum melting point, minimum dielectric strength and minimum heat deflection temperature. Compared to the first version, hardness was removed from this group and minimum melting point was added because hardness will need some more programming steps.

The second group is the (like values group). It includes four variables: colour, heat resistance, bio-compatible and water resistance. Compared to the first version, the bio-compatible variable has replaced sanitary conditions variable.

The third group is the (maximum values group). It includes four variables: maximum strength, maximum modulus, maximum melting point and maximum heat deflection temperature. For this group, the KBS obtains from the database a material list that has values less than or equal the required values set by users.

The fourth group is the (hardness group). In the second version, the hardness is a special case because in the first version the used hardness was the Shore D hardness and only the minimum value but in the second version includes two types of hardness which are: Shore D and Vickers. Furthermore, users can enter minimum and maximum value for any type of hardness. There is a constraint that user can select only one type when he enters the hardness values. if user enters a value for minimum Shore D hardness, automatically the boxes of Vickers hardness both minimum and maximum would turn inactive.

For the first group of variables the KBS connects to the database and gets a list of the materials (within the feasible processes) that their variable values exceed the required minimum variable. The same logic is used for the second group of variables except that when the KBS connects to the database, it gets a list of the materials (within the feasible processes) that their variable values are less than the required maximum variable. For example, if a maximum melting point is set by a user the KBS connects to the database and gets all the materials for which their melting point is less than or equal to the required melting point.

For the (hardness group) some new boxes in the flowcharts in Figure 6.16 and Figure 6.17 that need to be explained. These boxes tackle the hardness variable. First the KBS gets from the database a list of all the materials within the successful processes. Next, interpolation is done to transfer all the Vickers hardness to shore D hardness. Next, the two columns of the interpolated Vickers hardness and the shore D hardness are merged together to form one column in shore D hardness units.

There is now a new material list called material list (a) that has one Shore D hardness column. At this point a decision has to be made, the KBS checks if the user entered a shore D value or not? If not it means that he entered Vickers value.

Consequently, interpolation is used to transform the required Vickers value(s) to shore D value(s). Next, a list of the materials for which the hardness is greater than or equal to the required minimum hardness is retrieved from the database. A check is made if the material list of the hardness is empty, if yes the KBS adds to the reasons list that no AM material within the database could meet the required minimum hardness.

Next a list of the materials for which their hardness is less than or equal to the required maximum hardness is retrieved from the database. A check is made if the material list of the hardness is empty, if yes the KBS adds to the reasons list that no AM material within the database could meet the required maximum hardness.

Selecting material by class

When users choose to select material by class the window shown in Figure 6.15 appears. Users can select polymers, metals, or ceramics. If a user selects polymers the KBS connects to the database and all the materials that are classified as polymers. If a user selects metals the KBS connects to the database and retrieves all the materials that are classified as metals. Finally, if a user chooses ceramics the KBS connects to the database and retrieves all the materials that are classified as ceramics.

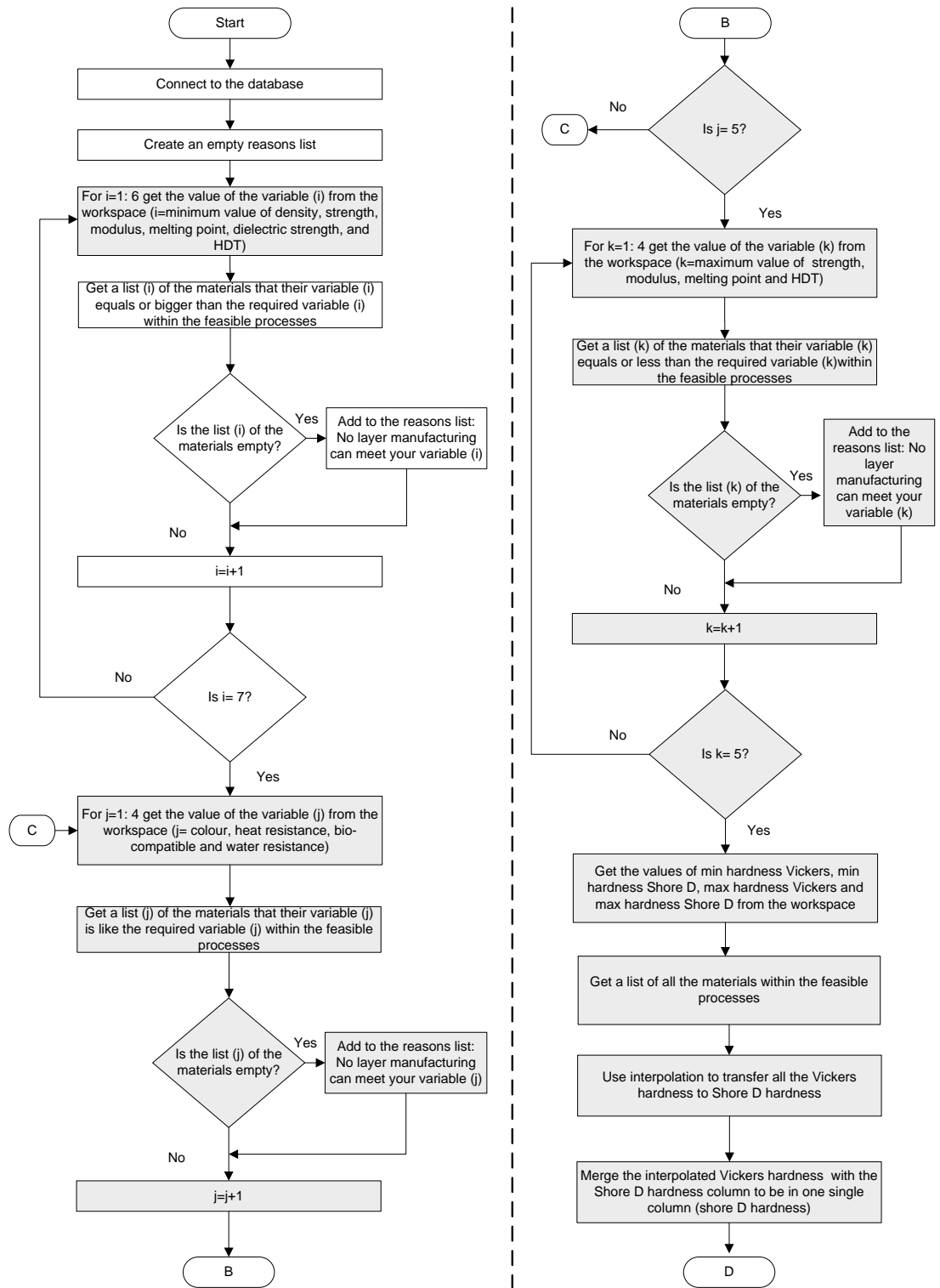


Figure 6.16: Checking AM Materials Flowchart (Version 2).

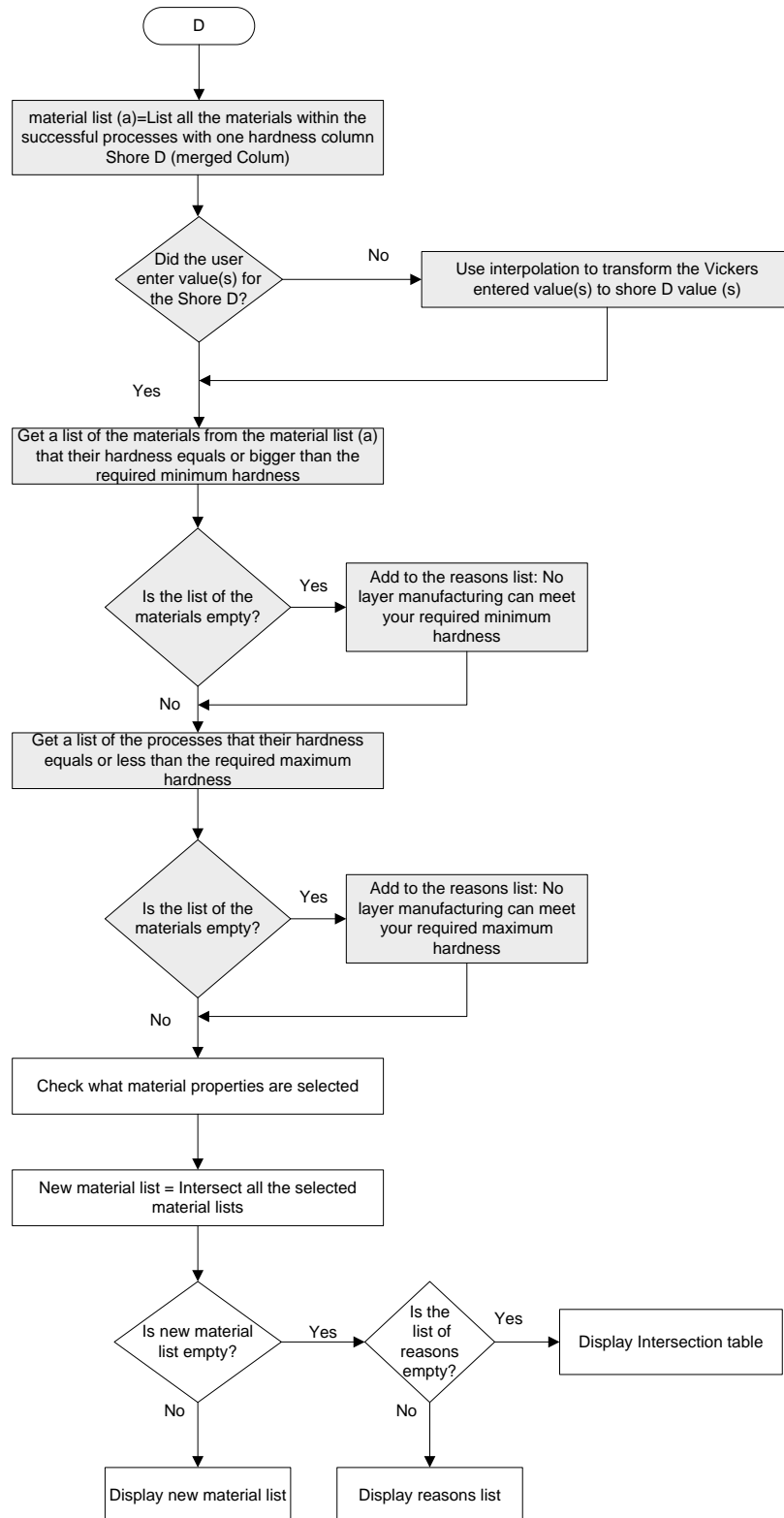


Figure 6.17: Checking AM Materials Flowchart (Version 2 Continued).

III. Ranking Element:

The third element in the KBS selection part is ranking. In the first version, the ranking was done considering that the maximum values are better than the minimum values. An important modifications in the second version is that the possibility that some criteria such as density, hardness and dielectric strength would be ranked in a reverted direction. This means that the minimum values are better than the maximum values. Some users would needs in their parts that lower density (and/or) lower hardness (and/or) lower dielectric strength is better. A new criteria screen was designed as shown in Figure 6.18. The new screen includes three radio buttons, when any of them is pressed means that the user needs to sort this criterion according to the minimum values are better than the maximum values.

Please give weights the following criteria according to their importance.
If you are not interested in any of the criteria leave the cell empty.

Use a Scale from 1 (Not Important) to 10 (Very Important)

Criteria	Weight
1- STRENGTH	<input type="text"/>
2- HARDNESS	<input type="text"/>
3- TEMPERATURE	<input type="text"/>
4- DENSITY	<input type="text"/>
5- DIELECTRIC STRENGTH	<input type="text"/>
6- MODULUS	<input type="text"/>
7- WALL THICKNESS	<input type="text"/>
8- ACCURACY	<input type="text"/>
9- SURFACE FINISH	<input type="text"/>

There are two options for ranking some of the criteria:

- 1- Ranking while considering that the maximum values are better.
- 2- Ranking while considering that the minimum values are better.

The default ranking method for all criteria is maximum values are better. When you select the radio button of a criterion you select that you prefer to rank this criterion according to the minimum values are better.

Density Hardness Dielectric Strength

Figure 6.18: Criteria Screen (Version 2).

Figure 6.19 and Figure 6.20 show flowcharts that explain how the SMART method was used. The modifications are shaded. The melting point (usually for metal or ceramics) of the material and the heat deflection temperature (usually for plastics) are merged together into one column called temperature column. Next the normalized value is calculated by dividing the temperature of each material to the maximum temperature in this column. The result is multiplied by ten.

The merging is done only if the material selection is by properties but if the material selection is by class the temperature column takes the heat deflection temperature column in case of polymers class and the melting point column in case of metals class and ceramics class without any merging.

Furthermore, to rank some criteria in another direction the logic is as follows: if a user presses a radio button for criterion (i) a variable called x (i) is assigned to 1. If the user does not press the buttons so x (i) is assigned to 0. If x (i) =1 then this equation is used:

$$\text{Norm.score value criterion (i)} = [[\text{Norm.score value criterion (i)} - 10] \times -1]$$

In order to the reverting process to take place, the new normalized score values take effect and replace the old normalized score values for the selected criteria and the ranking process continues normally after that.

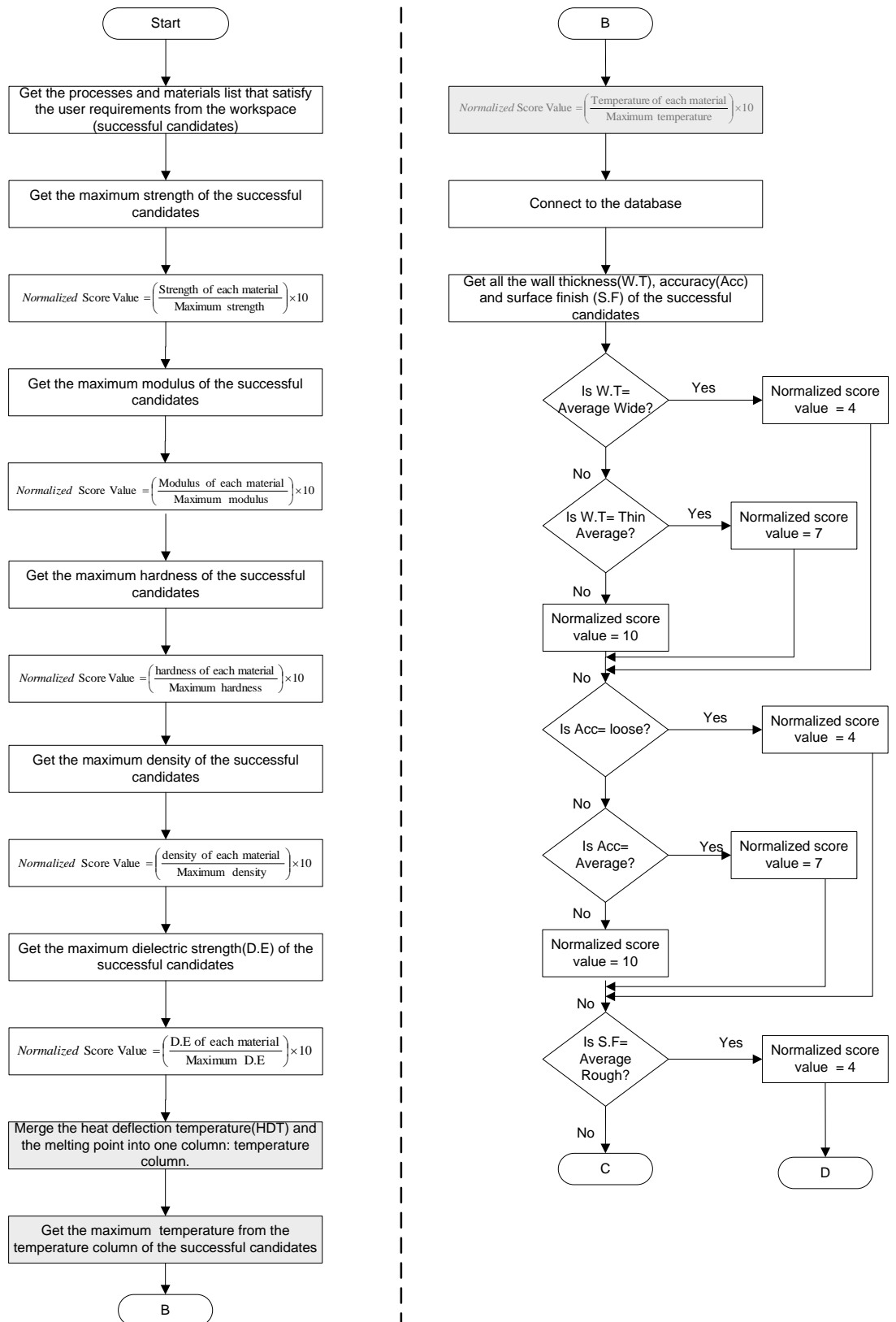


Figure 6.19: SMART Ranking Flowchart (Version 2).

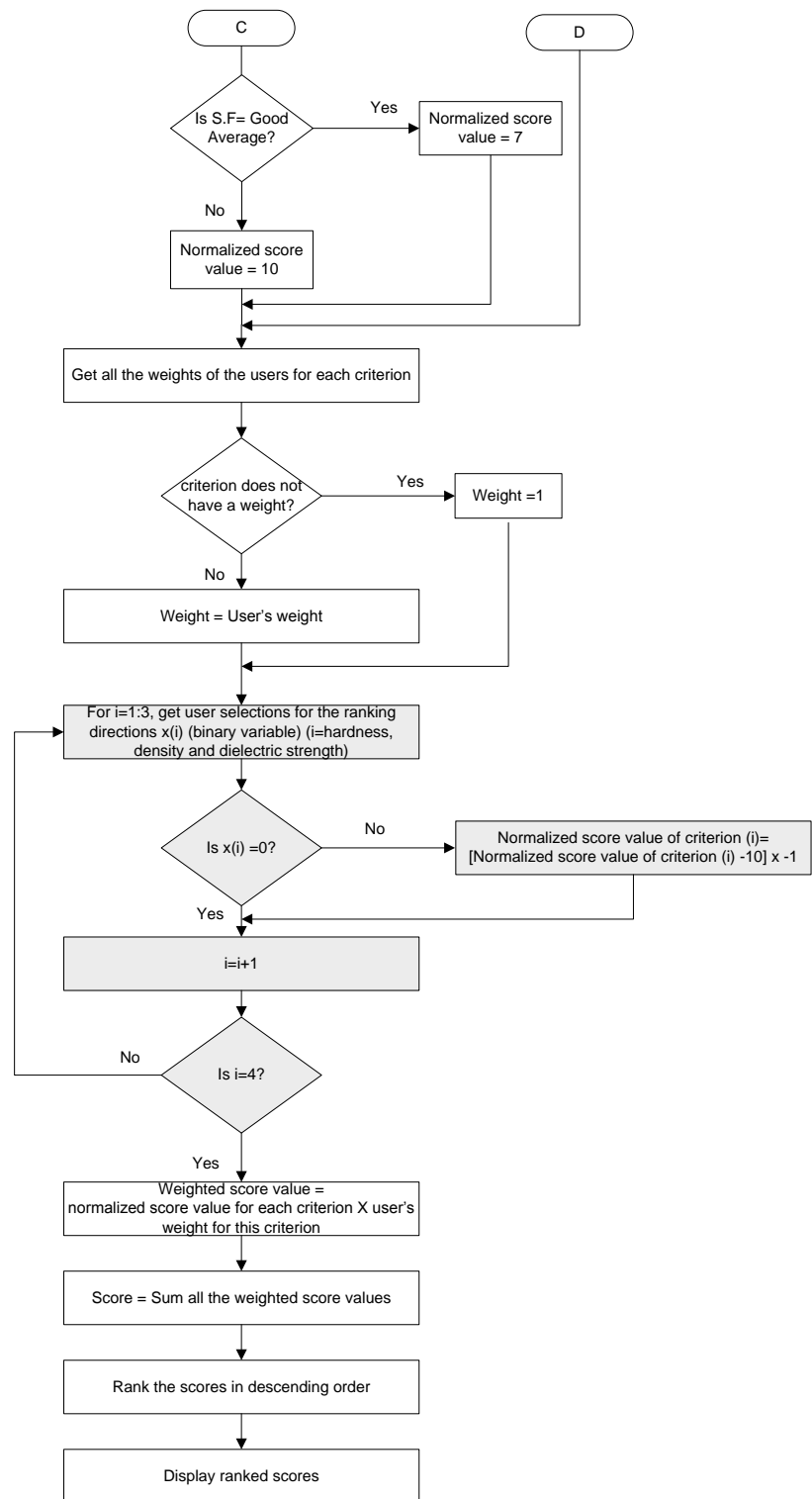


Figure 6.20: SMART Ranking Flowchart (Version 2 Continued).

After the KBS finished ranking a final ranking screen appears as shown in Figure 6.21. The processes and the materials are ranked in descending order. Users have four further steps appeared in the following order: 1- selects intermediate material

(in case the process needed an intermediate material), 2- selects finishing methods, 3- select machines and 4- goes directly to technical summary. Any step can be skipped. In addition a button was added for the users who which to see the SMART calculations in details as shown in Figure 6.22. This is a modified screen based on the feedback of the users. In the first version, users needed to make selections for the intermediate materials for example and then pressed back to the final ranking screen again and the same for the finishing and the machines. Many users did not like to go back after going forward. The second version made the AMDSS selections go into one direction and any step can be skipped based on user preferences.

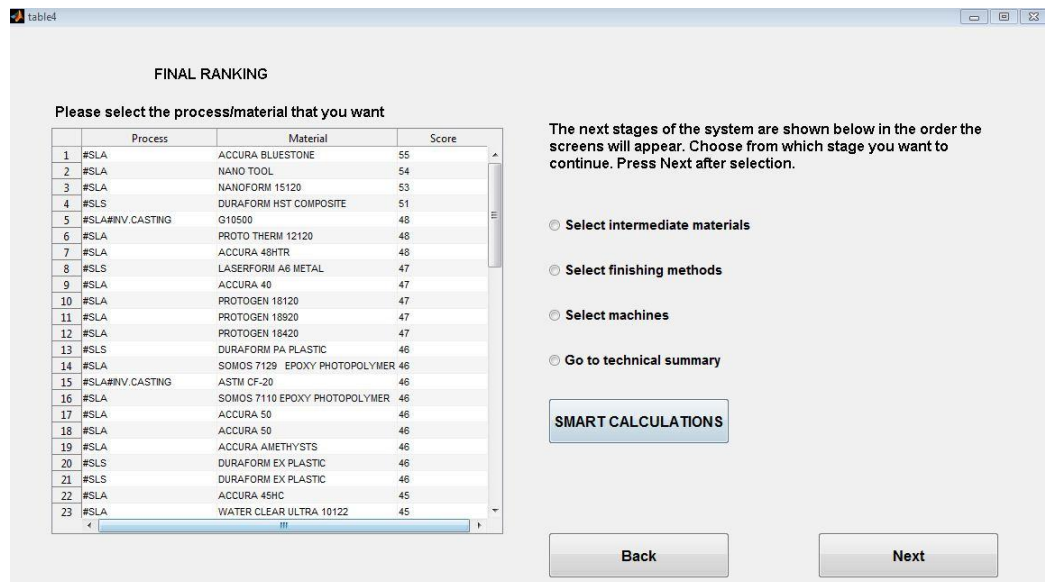


Figure 6.21: Final Ranking Screen of the AMDSS (Version 2).

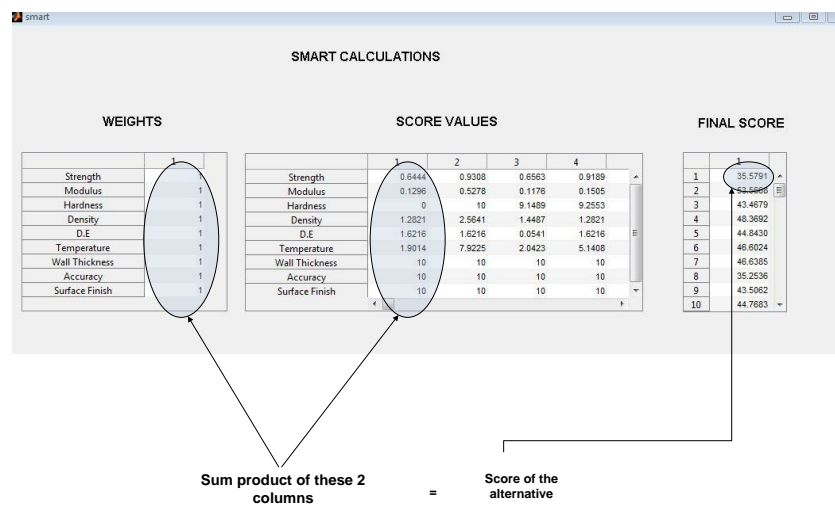


Figure 6.22: SMART Calculations (Version 2).

IV. Finishing Element:

The finishing element was changed in the second version of the AMDSS. First of all, the finishing table contains a finishing method path and not a single method. In addition, the finishing level that could be obtained from the finishing path is displayed. Furthermore, there is a general finishing advice that could help users in their selections of the best finishing methods. When a user selects a process like SLS for example, and then selects choose finishing methods the KBS connects to the database and gets all the finishing methods and the surface finish level that can be achieved. Figure 6.23 shows an example of the finishing options screen for the SLS process.

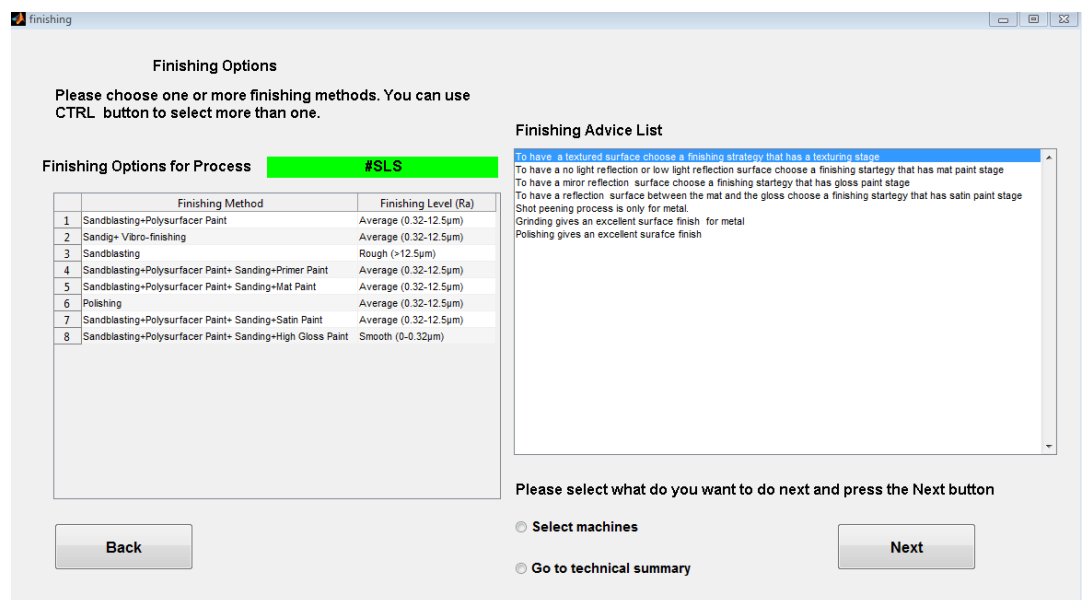


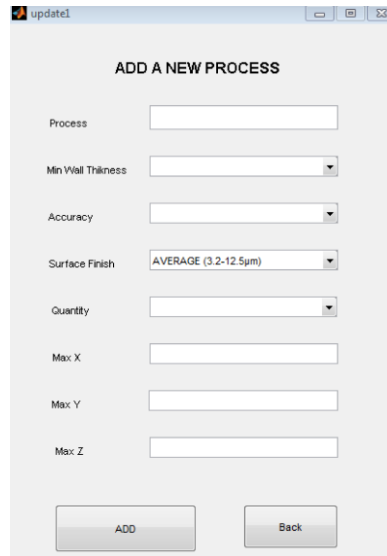
Figure 6.23: Finishing Options Screen in the AMDSS (Version 2).

2. Update Part Modifications

Due to the changes made in the selection part of the AMDSS, there were changes also made to the update part.

Add a process

The only thing that has been changed in the add a process screen is that the popup down menu of the surface finish input has changed to smooth (0 - 0.32 µm), average (0.32-12.5 µm) and rough (>12.5 µm) instead of excellent (0 - 0.32 µm), good-average (0.32-12.5 µm) and average rough (>12.5 µm) respectively.

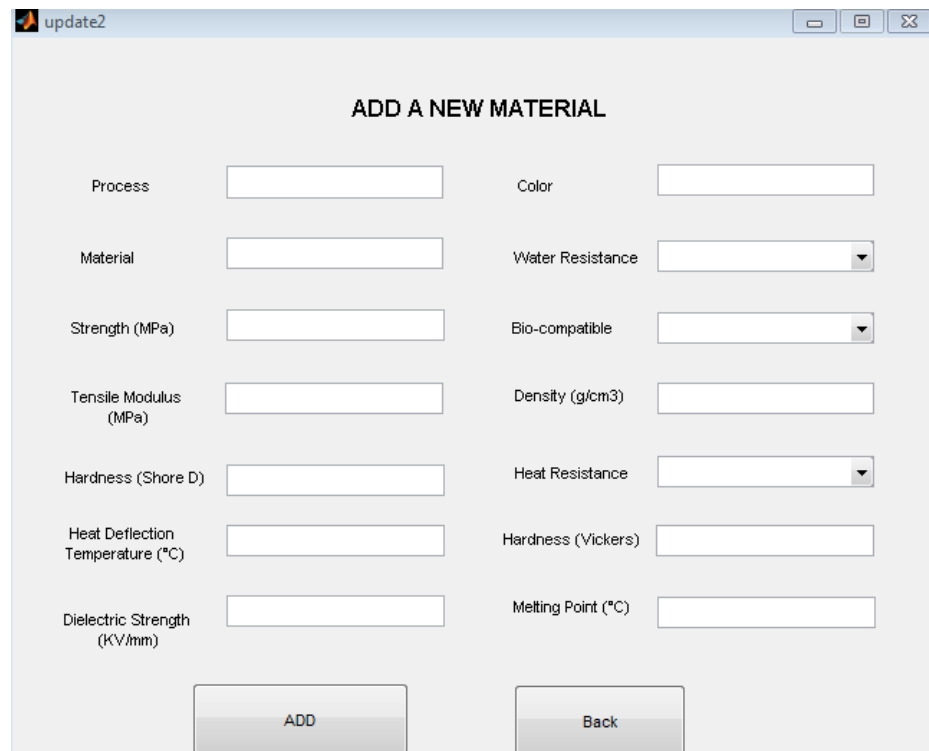


The screenshot shows a window titled 'update1' with the heading 'ADD A NEW PROCESS'. The form contains the following fields: 'Process' (text input), 'Min Wall Thickness' (dropdown menu), 'Accuracy' (dropdown menu), 'Surface Finish' (dropdown menu with 'AVERAGE (3.2-12.5µm)' selected), 'Quantity' (dropdown menu), 'Max X' (text input), 'Max Y' (text input), and 'Max Z' (text input). At the bottom, there are two buttons: 'ADD' and 'Back'.

Figure 6.24: Add a Process in the Database (Version2).

Add a new material

Figure 6.25 and Figure 6.26 show the modified add a new material screen and add a new intermediate material respectively. It can be shown that hardness Vickers and melting point was added. In addition, sanitary condition is replaced by bio-compatible. When user enters values for these variables the KBS connects to the database and adds the new material to the database with the given specifications.



The screenshot shows a window titled 'update2' with the heading 'ADD A NEW MATERIAL'. The form is organized into two columns of fields: 'Process' (text input), 'Material' (text input), 'Strength (MPa)' (text input), 'Tensile Modulus (MPa)' (text input), 'Hardness (Shore D)' (text input), 'Heat Deflection Temperature (°C)' (text input), 'Dielectric Strength (KV/mm)' (text input), 'Color' (text input), 'Water Resistance' (dropdown menu), 'Bio-compatible' (dropdown menu), 'Density (g/cm3)' (text input), 'Heat Resistance' (dropdown menu), 'Hardness (Vickers)' (text input), and 'Melting Point (°C)' (text input). At the bottom, there are two buttons: 'ADD' and 'Back'.

Figure 6.25: Add a New Material (Version 2).

Add a new intermediate material

The screenshot shows a software window titled 'update5' with the heading 'ADD A NEW INTERMEDIATE MATERIAL'. The form contains the following fields and controls:

Process	<input type="text"/>	Color	<input type="text"/>
Material	<input type="text"/>	Water Resistance	<input type="text"/>
Strength (MPa)	<input type="text"/>	Sanitary Conditions	<input type="text"/>
Tensile Modulus (MPa)	<input type="text"/>	Density (g/cm3)	<input type="text"/>
Hardness (Shore D)	<input type="text"/>	Heat Resistance	<input type="text"/>
Heat Deflection Temperature (°C)	<input type="text"/>	Hardness (Vickers)	<input type="text"/>
Dielectric Strength (KV/mm)	<input type="text"/>	Melting Point (°C)	<input type="text"/>

At the bottom of the form are two buttons: 'ADD' and 'Back'.

Figure 6.26: Add a New Intermediate Material (Version2).

Add a new finishing method

The last change is in the finishing update screen shown in Figure 6.27. It include process name which means the AM process name, finishing methods so the user can add a path and not a single method and finally the finishing level expected from this finishing path.

The screenshot shows a software window titled 'update4' with the heading 'ADD A FINISHING PROCESS'. The form contains the following fields and controls:

Process Name	<input type="text"/>
Finishing Methods	<input type="text"/>
Finishing level (Ra)	<input type="text"/>

At the bottom of the form are two buttons: 'ADD' and 'BACK'.

Figure 6.27: Add a New Finishing Method (Version2).

6.2 Second Feedback

The purpose of the second feedback was to make assessment of the second version of the AMDSS. The first feedback was for system improvement while the second feedback was more for the system evaluation.

6.2.1 *Second Questionnaire Design*

The questionnaire contains two parts: the first part is the user profile and the second part is general questions. The first part gives the researcher an overview about the user knowledge about the AM technologies and processes. The second part is a general question that gives information about the system overall by asking users about the advantages and limitations of the system. As previously discussed in chapter five, users were classified into two groups: advanced users and average users. According to this classification there were three advanced users and three average users. Table 6-2, Table 6-3, Table 6-4 and Table 6-5 show the second version questionnaire.

1- User Profile

Question1:

How often do you need to select additive manufacturing process or material?

- a. Weekly
- b. Monthly
- c. Sporadically
- d. Other:_____

Question2:

Have you used any knowledge based system for selecting additive process or material before? If yes please name it

Question3:

How do you normally select the following:

- a. Additive manufacturing process
- b. Material
- c. Finishing methods
- d. Machines

2- General Questions

Question1:

Would you like to add any information to any of the AMDSS screens?

Question 2:

Would you like to remove any information to any of the AMDSS screens?

Question3:

Did you find the AMDSS helpful when you have applied it to your case study for selecting:

- I. The possible process chains.
- II. Materials
- III. Machines
- IV. Finishing methods

Table 6-2: AMDSS Second Version Questionnaire (Page 1 of 4).

Question 4:

How important is the ability of updating the process chain, material, finishing and machines to you in an additive manufacturing DSS?

- a. Not Important
- b. Important
- c. Very Important
- d. Extremely Important

Question 5:

What elements do you like to add to the AMDSS?

Question 6:

What did you like most?

Question 7:

What did you dislike most?

Question 8:

How do you rate the following elements in the AMDSS:

Elements	Rating				
Process selection	Weak	Fair	Good	Very Good	Excellent
Material selection	Weak	Fair	Good	Very Good	Excellent
Intermediate material	Weak	Fair	Good	Very Good	Excellent
Finishing selection	Weak	Fair	Good	Very Good	Excellent
Machines selection	Weak	Fair	Good	Very Good	Excellent
Process update	Weak	Fair	Good	Very Good	Excellent
Material update	Weak	Fair	Good	Very Good	Excellent
Finishing update	Weak	Fair	Good	Very Good	Excellent
Machine update	Weak	Fair	Good	Very Good	Excellent
DSS clarity	Weak	Fair	Good	Very Good	Excellent
DSS length	Weak	Fair	Good	Very Good	Excellent

Table 6-3: AMDSS Second Version Questionnaire (Page 2 of 4).

Question 9:

Looking long term, do you think that the best form for a DSS of this type is:

- a. A stand alone application
- b. Online application
- c. A CAD Plug-in.
- d. Other (please state)

Question 10:

If you have used the first version of this system, how do you compare the 1st version to the 2nd version with regard to:

I. The process selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

II. The material selection:

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

III. Finishing selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

IV. Machine selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

Table 6-4: AMDSS Second Version Questionnaire (Page 3 of 4).

Question 11:

Please comment on the following capabilities of the AMDSS:

- I. Selecting material first or process first.
- II. Selecting by material class or by material properties.
- III. Determining minimum and maximum values of the material properties.
- IV. Helping on the finishing strategies selection.

Question 12:

Do you have any suggestions for improving the AMDSS?

Table 6-5: AMDSS Second Version Questionnaire (Page 4 of 4).

6.2.2 Second Questionnaire Observations and Analysis

The responses of the users were satisfactory in general and agreed that improvement happened. Some users have some remarks and suggestions. It has to be mentioned that these remarks are based on a relatively small sample (six users). The reason of the small sample was because the purpose of the second questionnaire was assessment rather than a feedback. In addition, some average and expert users who tested the system on the first time did not have the time to re-test it again. The following are some points that need to be underlined:

- There was a suggestion to add more machines. The system was designed to be updatable so any user can add his required machines.
- There was an opinion to remove some SLA materials from the database because the present list is very exhaustive. The system was designed to be editable so users can remove any things that they do not want. In addition, this is a general system so perhaps some users would like to have more options and choices.
- Most of users of the second questionnaire found the AMDSS helpful when they have applied it to their case studies and tried to make a selection regarding process chains, materials, machines and finishing methods.

- One user found the updating important, another user found it very important and four users found it extremely important.
- Some users suggested adding to the AMDSS: 1- matching engineering materials with AM materials, 2- costing and 3- mechanical properties variation versus build orientation.
 - 1- For matching: selecting material by properties let users enter values they need. If one user needs a specific engineering material he can feed the system with the properties and the system will show the AM materials that can manufacture the part.
 - 2- For costing: it is difficult to make a model that can be used because there is a big difference between cost and price.
 - 3- For adding mechanical variations versus build orientation: there is no enough data available for the materials. Many experiments have to be done for each material to build such database.
- Some users liked the improvements, the simplicity, the surface finish selection and the user assistance.
- No user disliked anything about the AMDSS second version.
- All the average and advanced users rated the process selection, material selection, intermediate material selection, process update, material update, finishing update, machine update, AMDSS clarity and AMDSS length from good to excellent.
- All users rated finishing selection and machine selection from good to excellent except one user who rated these two elements from weak to fair.
- For the best future form of the AMDSS stand alone application was chosen twice, online application was chosen four times and CAD plug-in was chosen four times.
- The only two advanced users who used the first version of the AMDSS had seen that the second version is better for process selection and

material selection. For the finishing selection and machine selection one user thought that the second version was like the first version and the second user thought that the second version is better.

- Most of users of the second questionnaire thought that adding the option of selecting process first or material first, selecting material by class and by properties, determining minimum and maximum values of the material properties, and helping on the finishing strategies was helpful and considered it a good improvement.
- One user suggested for improvement: adding material class such as polymers, metals and ceramics in the material list that appears to the user.

6.3 Second Version User Testing and Evaluation

In section 5.2 four users have tested the developed first version of the AMDSS with four parts that their selections was already made. The data of the four parts were fed to the system and a comparison was made to the AMDSS results with the real results. The selections of the first version were compatible with those of the real ones.

The screenshot shows a software window titled 'process' containing a 'PROCESS SELECTION' panel. The panel prompts the user to 'PLEASE SELECT ALL FIELDS' and lists several parameters with their respective values or selected options:

Field	Value/Option
LENGTH (mm)	140
WIDTH (mm)	87
HEIGHT (mm)	177
QUANTITY	ONE
ACCURACY	AVERAGE (0.1-0.25mm)
SURFACE FINISH	AVERAGE (0.3.2-12.5µm)
MIN WALL THICKNESS	THIN-AVERAGE (0.5-2mm)

Below the input fields, the calculated 'VOLUME (mm3)' is shown as $2.15586e+006$. This value is highlighted with an orange oval and labeled 'Volume Calculation' with an arrow. At the bottom of the panel are three buttons: 'RESET ALL VALUES', 'Back', and 'FIND SUITABLE PROCESSES'.

Figure 6.28: Process Selection Screen Showing Volume Calculation (Version 2).

The second version of the AMDSS was tested using the same inputs of the four parts. This testing was done by the researcher and not by the users of these case studies. The Selections of the second version for the four parts were the same selections of the first version but there are some improvements that need to be highlighted which are the adding of volume calculations, finishing paths and minimum and maximum property ranges.

Volume Calculations

While the first version of the AMDSS did not use the volume or showed to users, the second version showed the volume calculation of the part in the process selection screen when the user enters the values of the length, width and height as shown in Figure 6.28. The volume calculations for the four parts were as follows:

- Cover part = 2155860 mm³.
- Drain fitting part = 279923 mm³.
- Filter cover part = 657120 mm³.
- Dental part assembly = 16920 mm³.

Finishing Paths

While the first version of the AMDSS showed only finishing processes with very limited information, the second version showed finishing paths instead of just one finishing method.

Figure 6.29 shows the finishing paths for the cover part. The finishing path selected was sanding + sandblasting instead of sandblasting in the first version and the system showed the expected Ra level of the surface finish which was average level (Ra = 0.32 μm - 12.5μm). Furthermore, the finishing advice list was also an addition that gave advices to the users when making finishing selections.

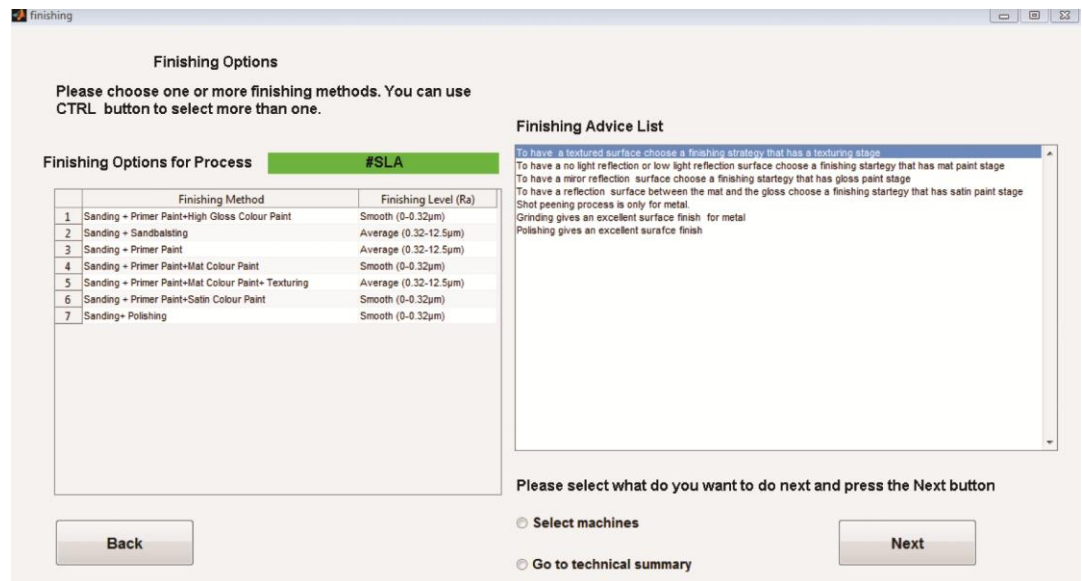


Figure 6.29: Finishing Options Screen for the Cover Part (Version 2).

The finishing options that included sandblasting method (selected in the first version) for the drain fitting part were six paths as shown in Figure 6.30:

- 1- Sandblasting (surface finish = Rough. Ra >12.5µm).
- 2- Sandblasting + Polysurfacer Paint (surface finish = Average. Ra = 0.32-12.5µm).
- 3- Sandblasting + Polysurfacer Paint + Sanding + Primer Paint (surface finish = Average. Ra = 0.32-12.5µm).
- 4- Sandblasting + Polysurfacer Paint+ Sanding + Mat Paint (surface finish = Average. Ra = 0.32-12.5µm).
- 5- Sandblasting + Polysurfacer Paint + Sanding + Satin Paint (surface finish = Average. Ra = 0.32-12.5µm).
- 6- Sandblasting + Polysurfacer Paint + Sanding + High Gloss Paint (surface finish = Smooth Ra = 0-0.32µm).

The second version gave the user six finishing paths so he could select between them and to know what would be the expected surface finish that he could obtain from each surface finish path.

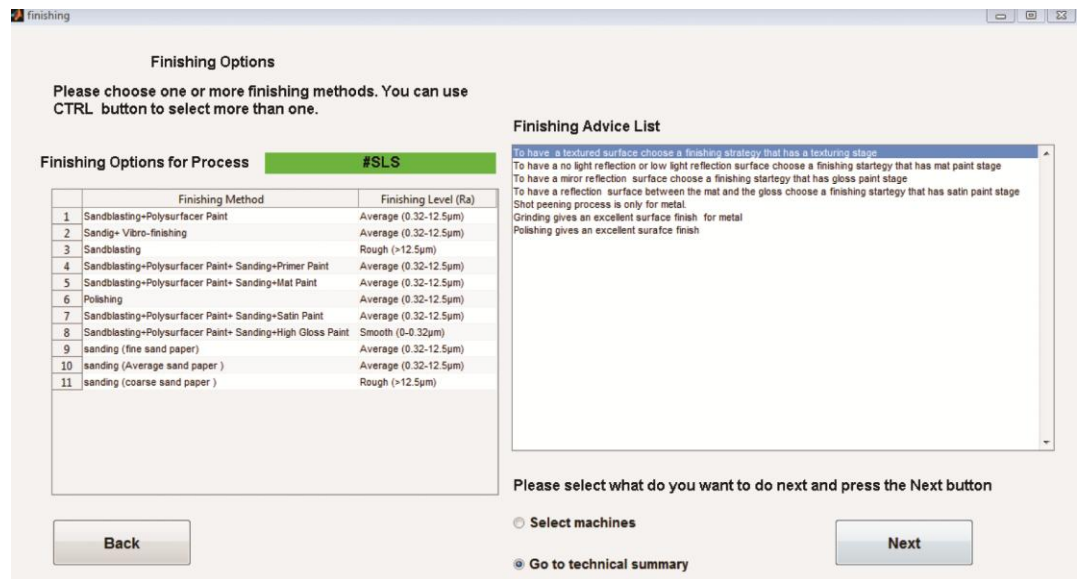


Figure 6.30: Finishing Options Screen for the Drain Fitting Part (Version 2).

The finishing options that included sanding method (selected in the first version) for the filter cover were four paths as shown in Figure 6.31:

1. Sanding + Vibro-finihing (surface finish = Average. Ra = 0.32-12.5µm).
2. Sanding (fine sand paper) (surface finish = Average. Ra = 0.32-12.5µm).
3. Sanding (Average sand paper) (surface finish = Average. Ra = 0.32-12.5µm).
4. Sanding (coarse sand paper) (surface finish = Rough. Ra >12.5µm).

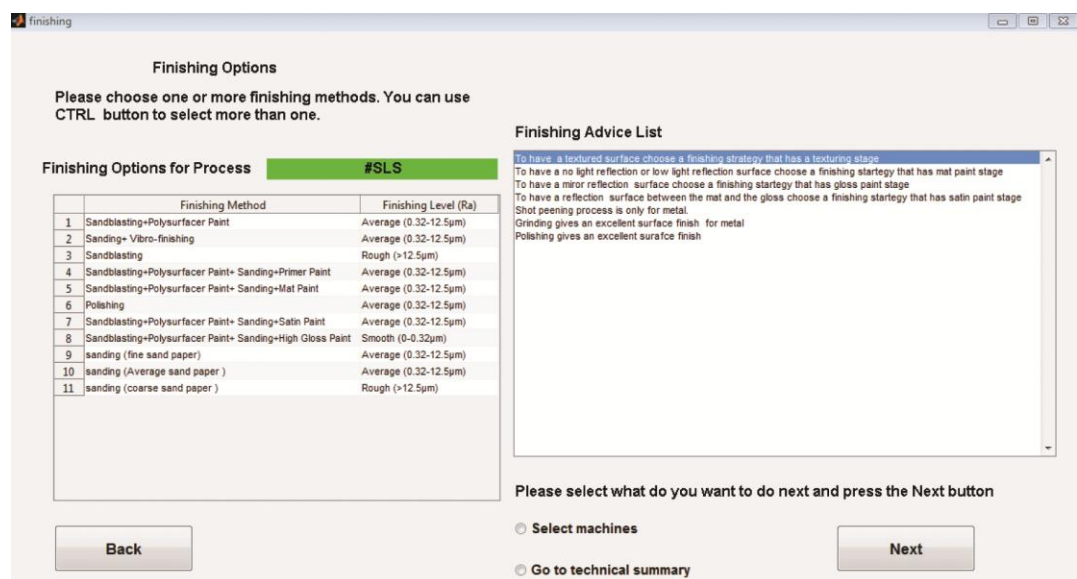


Figure 6.31: Finishing Options Screen for the Filter Cover Part (Version 2).

The finishing option for the dental part assembly as shown in Figure 6.32 had changed from polishing in the first version to a finishing path sanding + polishing. In addition, the surface finish expected was shown which was smooth ($R_a = 0 - 0.32\mu\text{m}$). The surface finish advice list shows an advice that says that polishing gives an excellent surface finish.

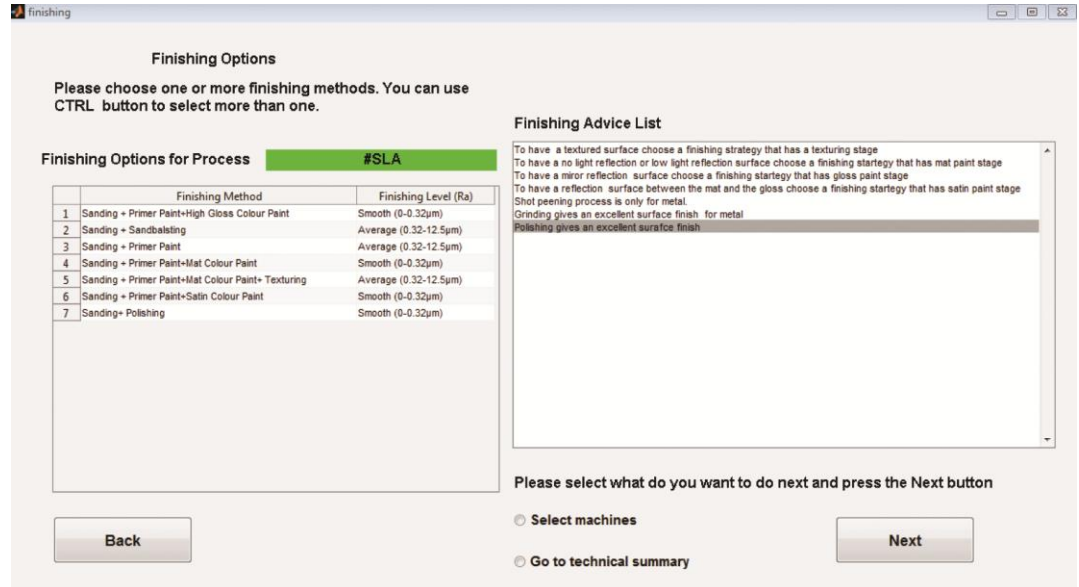


Figure 6.32: Finishing Options Screen for the Dental Implant Part (Version 2).

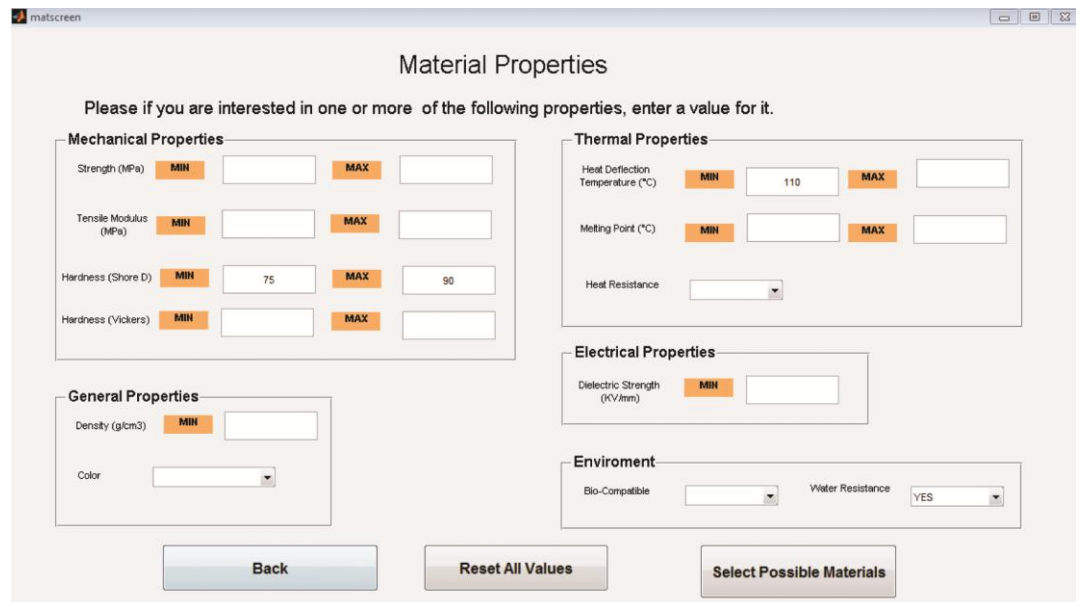


Figure 6.33: Material Properties Screen for the Filter Cover Part (Version 2).

Minimum and Maximum Material Property Ranges

While the Material and properties screen of the first version included only the minimum value of the different properties, the second version showed the minimum and maximum ranges of different properties.

In the first version, in the material selection for the filter cover part the user selected the minimum hardness to be 90 Shore D. There was a conflict between the black colour and the required hardness and because the part could be pigmented to black colour the user relaxed the colour constraint. This user in the first version asked for having the possibility of having ranges so the trade-off between the variables and compromising can be made. The user could accept a hardness range between a minimum of 75 Shore D and a maximum of 90 Shore D. In the second version, the user had the possibility to enter the two ranges as shown in Figure 6.33.

Comments:

There are some remarks that need to be underlined from testing the second version of the AMDSS using the four parts provided by users:

- The volume was shown in the process selection when users entered the part dimensions. The AMDSS checks this volume against the different process maximum volumes. Some users asked for the volume to know the amount of material needed and to use it for costing and to check how many parts could a machine do in one build.
- Users had the option to select between selecting materials by properties and selecting materials by classes. Users of the four parts have already some specified value of one or more property so selecting material by classes was not used.
- Users had the option to select process first or material first. This study tried both routes and the results were the same.
- The filter cover part showed how users can benefit from the minimum and maximum ranges.

- The finishing options in the system was improved by giving the possibility to have finishing paths instead of a single finishing method, providing Ra level and providing finishing advice that could help in the selection.

Chapter 7. Discussion

7.1 Summary of the Work

The need for an automated procedure for the selection of AM processes and materials to meet the requirement of a desired component was the main motive of this research. A system called AMDSS (additive manufacturing decision support system) was developed. Nine main steps were used to achieve this goal: 1- analyzing the selector systems, 2-identifying their shortcomings, 3- indentifying target specifications, 4- developing the system, 5- verifying and validating the system, 6- obtaining feedback from users, 7- improving the system based on feedback, 8- obtaining a second feedback for the improved system from users and finally 9- launching the system.

7.1.1 *Selector System Shortcomings*

The selectors were classified into three types which are: 1- rapid prototyping selectors, 2- rapid manufacturing selectors and 3- rapid tooling selectors. The number of discussed systems and methodologies developed were eleven studies for rapid prototyping, ten studies for rapid manufacturing and eleven studies for rapid tooling. Out of all the above studies only eighteen produced developed systems, the rest were proposed methodologies. A comparison was made between the eighteen developed systems. Among these eighteenth systems, six are for RP selection only, four for RT selection only, five for both RP and RM selections, one for both RP and RT selections and two systems for RP, RT and RM selections.

Through the investigation of the developed systems the following shortcomings were identified:

1. While only two developed systems were able to perform general selections (RP, RT and RM), one of them lacked material selection and could not be updated by users and the second system was a general guide rather than a selector.

2. In most of the developed systems users cannot update the system database and if they can do so there is a need to change the programming logic which makes the systems obsolete after a while.
3. Many systems lacked material selection.
4. Most systems focused on processes only or machines only but there was no integration between process chains, materials, finishing methods and machines for a specific product.
5. Systems did not give reasons if a solution was not found.
6. Involvement of the users in the development of the selectors was not present.
7. Although selection of processes and materials affect each other, there was no ranking for processes and material together.

7.1.2 *Target Specifications*

Using the shortcomings of the developed selectors seven target specifications were set in chapter three:

1. Selecting the possible AM process chains, materials, finishing methods and machines.
2. Giving reasons if the system could not give a solution or satisfy users' requirements.
3. Ranking processes and materials according to user criteria.
4. Ability of being updated.
5. Ability of being customized.
6. Being simple, usable and customer focused.
7. Being product focused.

7.1.3 *AMDSS First Version Development*

Different architectures were considered and finally knowledge based system (KBS) and database (DB) architecture was selected because it could achieve the system target specifications. KBS and DB together form a versatile tool that contains flexible rules (If-Then) that uses variables and not constants. The KBS retrieves the data from the database depending on the user entry. The flexibility of the rules prevents the AMDSS system from becoming obsolete.

Three components form the structure of the AMDSS which are: 1- graphical user interface (GUI), 2- knowledge based system (KBS) and 3-Database (DB). Users use the GUI to input data and get the required information or advice. The KBS contains the programming logic and the database contains information about AM processes, materials, intermediate materials, finishing options and machines. IDEF0 and flowcharts tools were used to structure the system.

The KBS within the AMDSS consists of three main parts: 1- selection part, 2- browse part and 3- update part. The selection part helps users to select processes, materials, intermediate materials, finishing options and machine. The browse part helps users to explore the different processes and materials available in the database. The update part helps users to update the database.

7.1.4 *System Verification and Validation*

The AMDSS was verified to be sure that it was working properly and that the programming logic was correct. Different scenarios were proposed, the input-output relationships were tested and the result was that the system worked properly and logically.

Three industrial case studies were used for validation: 1- razor blade case study, 2- automotive case study (1) and automotive case study (2). The input parameters were fed to the AMDSS and the results were compared to the selections made in consultation with experts and both selections were compatible with each other.

7.1.5 *First Feedback*

A questionnaire was designed and the first version of the AMDSS was tested with thirteen users (nine of them average users and four advanced users). In addition, four users tested the AMDSS with four products already manufactured. The outputs of the AMDSS confirmed to the selections of the users

The responses of the users to the questionnaires were analyzed. They have outlined some weak points regarding the AMDSS system. The key points from the first feedback of users were:

1. AM selectors are not popular among average users and experts because they are obsolete. Users select AM processes in an ad-hoc way, or using websites or by asking service bureau which give them what they want to sell and what they know and not the optimum solution to the problem.
2. Some users preferred to select material before selecting process and this was not possible in the first version.
3. Some users liked to select materials by class and not by property screening.
4. Most of the users found the first version of the AMDSS was helpful in the selection of the process chains, materials and machines but not the finishing methods selection.
5. Most of the users rated the updating possibility in the system from important to extremely important.
6. Most of the users liked the simplicity and the small number of steps of the developed AMDSS.
7. Many users disliked that there was no ranges for material properties (minimum and maximum values).
8. Users prefer to have an AM system in the following forms in the following order: 1- online, 2- CAD plug-in, 3- standalone.

7.1.6 *AMDSS Second Version Development*

Thirteen modifications were made to the first version: 1- possibility of selecting process first or material first, 2-possibility of selecting material by class, 3-volume calculation of the part, 4- re-arranging the order of some inputs in the process screen, 5- renaming surface finish ranges, 6- adding the maximum values for some inputs of material properties, 7- adding hardness Vickers and melting point to the material properties screen, 8- replacing sanitary condition with bio-compatible, 9- changing sequence of some windows, 10- improving the finishing selection by adding finishing path, finishing level (Ra), and finishing advice that could be updated, 11- changing the updating panel to match the modifications and 12- adding help screens and 13- possibility of reverting the direction of sorting for some criteria such as hardness, density and dielectric strength.

The effect of these changes on the programming logic was expressed using IDEF0 and flowcharts.

7.1.7 *Second Feedback*

The purpose of this step was mainly assessment more than a feedback. A second questionnaire was designed which was a modified version of the first questionnaire. Six users responded to the second questionnaire, three of them were average users and three of them were advanced users. Two out of the six users have responded to the first version of the questionnaire and both were considered advanced users.

The responses of the users were analyzed. In general, the analysis of the responses of the users showed that the second version is an improved version by covering the weak points in the first version. The key points of the second feedback of users were:

1. Most of the users found that the second version of the AMDSS was helpful in the selection of the process chains, materials, machines and the finishing methods.
2. All users rated the updating possibility in the system from important to extremely important.

3. Some users liked the AMDSS improvements, others liked the simplicity and others liked the surface finish selection option.
4. Users preferred to have an AM system in the following forms in the following order: 1- online, 2- CAD plug-in, 2- standalone. The online and the CAD plug-in were chosen the same number of times.
5. Most users found that adding the option of selecting material first or process first is a good improvement.
6. Most users found that adding the option of selecting material by class or by properties is a good improvement.
7. Most users found that adding material ranges (minimum and maximum values) is a good improvement.
8. Most users found assistance with the finishing options is very useful.

7.1.8 *AMDSS Limitations*

Despite the satisfaction of some users who tested the system regarding the developed AMDSS, it does not come without its limitations. These limitations are:

- The system did not include any costing because there is a big difference between cost and price. If the system gives an advice based on cost and then the user went to a service bureau and was quoted a figure based on price so this would be a misleading piece of information.
- The system did not include geometry consideration, believing that AM processes can produce complex geometries.
- The information presented in the database was based on information from vendors' websites, papers and service bureaus. The accuracy of the data may not be as accurate as it should be but getting independent materials data for every material can only be done by experiment which would be very costly and time consuming.

- Material isotropy was not considered because of material data unavailability.
- Some material properties were not considered because of data unavailability (such as compressive strength, flexural modulus, environmental impact, hygroscopic property and porosity).
- The process selection calculates the volume of the required part and the build volume of the process and compares them. If the build volume is greater than the required part than the process is considered as one of the possible alternatives. Optimum build orientation was not considered.
- Building time was not considered because it differs from a part to another and parametric calculations give inaccurate figures.

7.2 Research Contributions

The main research contributions are:

- 1- Developing and evaluating an AM selector system using knowledge based system (KBS) and Database (DB) architecture with the following characteristics:
 - i. Integrated system that could select process chains, materials, finishing methods and machines covering RP, RT and RM areas.
 - ii. Updatable without the need to change programming logic to avoid embedded obsolescence. Users can update the information in the database such as processes, materials, intermediate materials, machines and finishing options. The system logic cannot be update, for example users cannot define a new wall thickness level or add a new material property or add their own criteria.
 - iii. Explaining the reasons for not being able to make a selection from the database if a selection could not be made.
 - iv. Ranking processes and materials together because they influence each other.

- 2- The involvement of users in the development stage of the AMDSS which is an important issue so that the developed selector represents their needs and not only the point of view of the developer.

7.3 Possible Future Forms of AMDSS

The two versions of the questionnaire asked users to select between four possible future forms of the developed AMDSS: 1- a standalone application, 2- CAD plug-in, 3- Online application and 4- others (to be specified by the user). Users can select more than one answer.

In the first version, stand-alone was chosen four times, online was chosen eight times, CAD plug-in was chosen six times. In the second version, stand-alone was chosen two times, online was chosen four times and CAD plug-in was chosen four times. Combining the two results give the selection of stand-alone six times, the selection of online twelve times and the selection of CAD plug-in ten times. The preferences in order are: 1- online, 2- CAD plug-in and 3- stand alone.

7.3.1 *Standalone Application*

The AMDSS has been developed in the Matlab environment. Matlab has a deployment tool that compiles the developed program so that it can work as a stand-alone application outside Matlab. The deployment tool starts a new empty project file that the developer adds to it all the .m files (Matlab coding files) and the .fig files (Matlab figure files) that form the complete program. The final result is an executable file that can be opened on any computer. Within the developed project Matlab added a compiler installer file called MCRInstaller.exe. Users have to run the installer at any computer only once before running the executable file. Another issue is that the developed AMDSS uses the visual query builder toolbox embedded in Matlab. The toolbox connects to the database through ODBC data source administrator. Users have to define the database used in the program in windows before running the executable file as shown in Figure 7.1 .

Certainly, the used method to transform the Matlab program to a stand-alone application is not the best option because when a user needs to run the developed program he has first to download the Matlab compiler on his machine and also add the database file using ODBC source administrator. Software companies can take the framework and the programming logic using the provided IDEF0 and

flowcharts and develop an AM selector using any advanced versatile programming language.

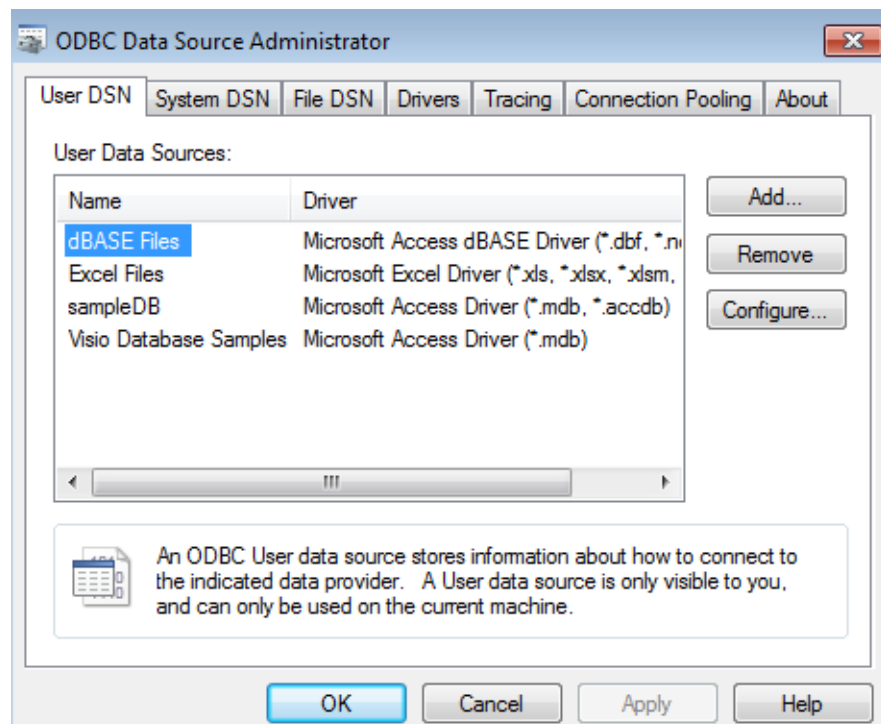


Figure 7.1: Adding ODBC Data Source in Windows

7.3.2 CAD Plug-in

Many users asked to have a CAD plug-in that could take the information required from the drawing file and analyze it. The program can work in the CAD environment as a start point. For example, Smith and Rennie (2010) have developed a knowledge system contained within a CAD environment (Solidworks) to select AM materials and processes. The screening is based on geometrical part features. The system screens the feature tree of a part, find features and compare each feature values against the saved values of the feature that an AM material and process is suitable for. It is an iterative process that is repeated until all the features are checked and at the end users have a list of materials that could manufacture the part. Users can render the part so they can view an estimation of the part.

In the case of the developed AMDSS, the information that could be retrieved is length, width, height and wall thickness of a given part. A menu could be added in the CAD software that could capture all the information needed. Next, the AMDSS starts within the CAD and users make their selections. After selecting the

process and materials, the part can be rendered within the CAD again so users can imagine how the part will look like.

7.3.3 *Online Application*

It is very obvious that the future trend is moving more and more towards an online world not only in AM process selection but in every field and domain. The idea of accessing the information from any place and from any computer or mobile phone is interesting for users.

In the literature there are some researchers that have used the idea of internet based rapid prototyping but this was for providing users with direct remote access to RP facility over the internet (sometimes called RP Tele manufacturing). The activities of these web-based RP-RM platforms include: process selection, price quotation, .STL viewer, RP data re-processing, job scheduling, remote control of AM machines, security management and applying new technologies. A good review of this direction of research could be found in Lan (2009). There is no focus on process selection in these types of studies; their focus is mainly on the system architectures.

Few researchers addressed the idea of the online selection of additive manufacturing. The available online application for selection are: 1- The RP selector developed by the IVF Sweden 2005 (IVF,2005), 2- The IRPDMS developed by (Mahesh et al.,2005), although the webpage is not available, 3- The decision support system for RP selection developed by (Lan et al.,2005) and 4- The KARMA project (ongoing FP7 project) (KARMA,2010).

Chapter 8. Conclusions and Future Work

The aim of this research was to develop an additive manufacturing decision support system that is capable of evaluating and selecting the most appropriate AM processes to meet the requirements of the desired component. This aim has been achieved by developing the AMDSS, which is a general AM selector system that helps users to select AM process chains, materials, intermediate material, finishing methods and machines. This chapter discusses the conclusions that can be drawn out of this study and suggests some possible future work.

8.1 Review of Objectives

This section describes the achievement of the five main objectives of the research.

1. Exploring different additive manufacturing processes and examining the most up to date information about new technologies in this field, and the most widely used by industry.

To develop the system, different AM processes and process chains were examined. The database developed (described in chapter three) included 14 of the most popular processes and process chains in the industry.

2. Exploring different additive manufacturing materials, machines and finishing options.

To develop the system, different AM materials, machines and finishing options were examined. The database developed (described in chapter three) included 133 materials, 10 intermediate materials, 52 machines and 44 finishing paths.

3. Using decision analysis tools to make selection among different layer manufacturing technologies and processes.

Chapter three discusses the use of IDEF0 and flowcharts to develop and describe the first version of the developed selector. In addition, chapter six discusses the also the use of the IDEF0 and flowcharts to develop the second version of the developed selector.

4. Developing a system that is capable of assisting decision makers in:
 - I. Determining the feasibility of additive manufacturing processes for a particular application.
 - II. Selecting the most suitable process.

The AMDSS was developed using KBS + Database architecture and was capable of determining if the processes were able to manufacture certain component or not and if not the AMDSS gives reasons for users why AM is not a suitable process. In addition, the processes and materials was ranked using SMART method according to the criteria of users so users can select from the final list the process and material that are suitable for their components . In addition, users can select intermediate materials, finishing options and machines. Chapter three and chapter six discuss the selection of the first and the second version of the AMDSS respectively.

5. Testing the developed system by applying verification and validation methods.

Testing the system was done through different methods: 1- verifying of the system to be sure that it is working correctly by checking system logic and comparing calculations done by the system with calculations done in spreadsheets and this was explained in chapter four, 2- validating of the system with three case studies in chapter four, 3- testing the system with users through interviewing users and making two versions of questionnaires described in chapter five (first version) and six (second version) and 4- making four users to validate the system with their components described in chapter five.

8.2 Conclusions

The following conclusions can be drawn out of this research:

1. AM selectors could be very useful for inexperienced and average users in order to help them to select processes, materials, machines and finishing paths if they are developed in a manner that represent the user's needs.

2. The updatability issue in any AM selector is very important and prevents the system from becoming obsolete. It has been achieved by using the flexible if-then rules.
3. Knowledge Based System (KBS) and Database (DB) architecture is considered a versatile architecture for the development of an updatable additive manufacturing decision support. This architecture could also be used for any decision support system and not only for AM selections.
4. The involvement of users in the development stage of AM selector is essential so the developed system represents the point view of users and not only developers.
5. Users prefer to have an online AM selector and also a CAD plug-in rather than a standalone application.

8.3 Future Work

The possible future work includes:

1. Developing a standalone system professionally to be a simpler, more user-friendly and more attractive selector system.
2. Integrating the developed system into different CAD environments so designers are comfort with the use of such a system. For example, adding the possibility to read .stl file instead of entering the data manually so the system could define the part width, length, height and minimum wall thickness.
3. Developing an online system based on the developed AMDSS using the three-tier architecture. The online system should have an online database that could be updated by experts so the data in the database become accurate and users can rely on.
4. Linking other modules to the system such as developing optimum building scenarios for different processes using different materials. A general AM process planning is required.
5. Adding a library that contains known solutions to known problems and use case based reasoning approach for the new problem to find a similar

problem and in result a similar solution. If this work could be done online, there could an online library that contains solution for different problems. This could be a very good pool for new users.

6. Developing a system that includes AM processes and conventional processes.
7. This work has addresses only the problem of the AM selection problem but there are other two types of problems that still need more work: 1- capital investment support and 2- process planning support. A system that could incorporate all the three types of problems will be a good step through a complete AM solution.

Appendix A. First Questionnaire Responses

1- User profile

This part contained three questions.

Question 1:

How often do you need to select additive manufacturing process or material?

- a. Weekly
- b. Monthly
- c. Sporadically
- d. Other: _____

Answers:

The answers to this question are summarized in Table A-1.

Advanced Users		Average Users		All Respondents	
Weekly	4/4	Weekly	1/9	Weekly	5/13
Monthly	0/4	Monthly	3/9	Monthly	3/13
Sporadically	0/4	Sporadically	5/9	Sporadically	5/13

Table A-1: Responses to User Profile Part Q1.

Question 2:

Have you used any knowledge based system for selecting additive process or material before? If yes please name it.

Answers:

Two advanced users answered yes and the other two answered no. One of the users who answered yes mentioned that he has used Matweb and AM materials selector. These two selectors are general selectors and not specialized in AM. The second user stated that he has used two AM selectors: the first one he did not remember the name, the second one is “Proto Selection”. All the nine average users answered no. The answers to this question are summarized in Table A-2.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	0/9	Yes	2/13
No	2/4	No	9/9	No	11/13
No Answer	0/4	No Answer	0/9	No Answer	0/13

Table A-2: Responses to User Profile Part Q2.

Question 3:

How do you normally select the following:

- a. Additive manufacturing process
- b. Material
- c. Finishing methods
- d. Machines

Answers:

- a. Additive manufacturing process

The answers to this question are summarized in Table A-3.

Advanced Users		Average Users		All Respondents	
Own Experience	2/4	Own Experience	2/9	Own Experience	4/13
Product Needs	1/4	Product Needs	5/9	Product Needs	6/13
Cost/Lead Time	1/4	Cost/Lead Time	1/9	Cost/Lead Time	2/13
Service Bureau's Recommendations	0/4	Service Bureau's Recommendations	1/9	Service Bureau's Recommendations	1/13

Table A-3: Responses to User Profile Part Q3a.

- b. Material

The answers to this question are summarized in Table A-4.

Advanced Users		Average Users		All Respondents	
Own Experience	2/4	Own Experience	2/9	Own Experience	4/13
Product Needs	2/4	Product Needs	5/9	Product Needs	7/13
Cost	0/4	Cost	1/9	Cost	1/13
Service Bureau's Recommendations	0/4	Service Bureau's Recommendations	1/9	Service Bureau's Recommendations	1/13

Table A-4: Responses to User Profile Part Q3b.

c. Finishing methods

The answers to this question are summarized in Table A-5.

Advanced Users		Average Users		All Respondents	
Own Experience	2/4	Own Experience	2/9	Own Experience	5/13
Product Needs	1/4	Product Needs	6/9	Product Needs	6/13
Service Bureau's Recommendations	0/4	Service Bureau's Recommendations	1/9	Service Bureau's Recommendations	1/13
In-house capability	1/4	In-house capability	0/9	In-house capability	1/13

Table A-5: Responses to User Profile Part Q3c.

d. Machines

The answers to this question are summarized in Table A-6.

Advanced Users		Average Users		All Respondents	
Build Size	2/4	Build Size	0/9	Build Size	2/13
Build Time	0/4	Build Time	1/9	Build Time	1/13
Availability	1/4	Availability	2/9	Availability	3/13
Product Needs	0/4	Product Needs	3/9	Product Needs	3/13
Knowledge	0/4	Knowledge	2/9	Knowledge	2/13
Service Bureau Recommendations	0/4	Service Bureau Recommendations	1/9	Service Bureau Recommendations	1/13
No Difference	1/4	No Difference	0/9	No Difference	1/13

Table A-6: Responses to User Profile Part Q3d.

2- AMDSS Screens

This part of the questionnaire asked about the main AMDSS screens. It contained eight questions that addressed eight main screens: 1-process screen, 2-material properties screen, 3- criteria weighting screen, 4- final ranking screen, 5- process update screen, 6- material update screen, 7-machine update screen, and 8- finishing options update screen. Each question contained one or more sections like: information section, terminology section, screening methods section, and scoring results section. Each section contained one or more sub-questions.

Question 1: Process screen

The first question asked about the process screen shown in Figure A-1. It contained two sections which were: information section and terminology section.

i. Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

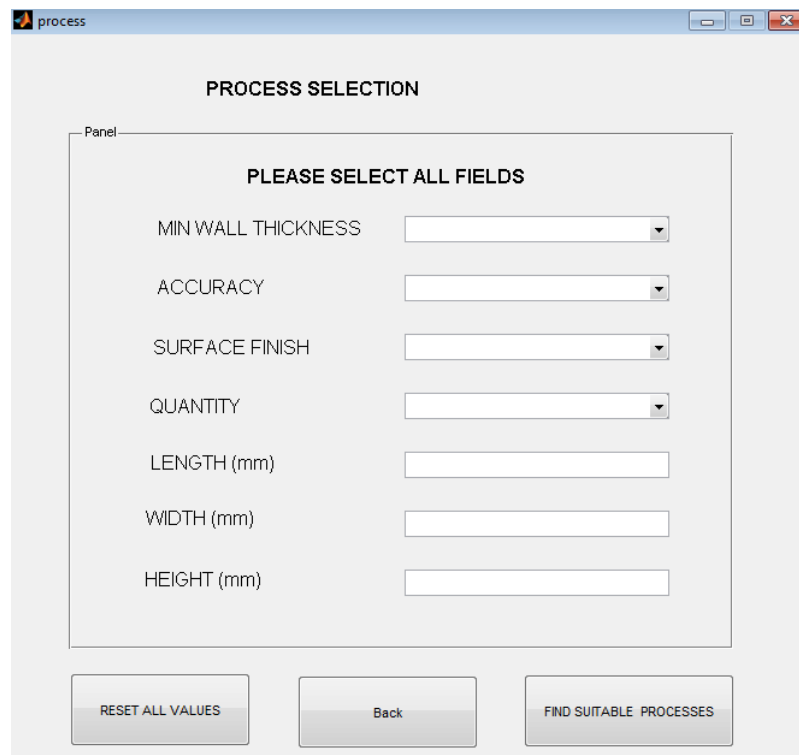


Figure A-1: Process Selection Screen.

Answers:

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-7.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	8/9	Yes	12/13
No	0/4	No	1/9	No	1/13
No Answer	0/4	No Answer	0/9	No Answer	0/13

Table A-7: Responses to AMDSS Screens Part Q1a (Information Section).

b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-8.

Advanced Users		Average Users		All Respondents	
Yes	1/4	Yes	7/9	Yes	8/13
No	3/4	No	2/9	No	5/13
No Answer	0/4	No Answer	0/9	No Answer	0/13

Table A-8: Responses to AMDSS Screens Part Q1b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-9.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	4/4	No	7/9	No	11/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-9: Responses to AMDSS Screens Part Q1c (Information Section).

d. Are there any fields that you would add?

Two advanced users said yes without specifying specific field, the other two said yes with the first one would like to add part volume and the second one would like to add delivery time. One average user did not answer, six did not want to add anything, one wanted to define the build platform shape, and one wanted to add overhung feature and make a decision on the support method for every thin feature. The answers to this question are summarized in Table A-10.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	2/9	Yes	6/13
No	0/4	No	6/9	No	6/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-10: Responses to AMDSS Screens Part Q1d (Information Section).

ii. Terminology Section

1- Do you think that the terminology used in the following drop down menu is easy to understand? Use the scale give below each term.

[1= difficult to understand and 5 =easy to understand.]

- Min wall thickness

(Very-Thin 0-0.5mm) / (Thin-Average 0.5-2mm) / (Average-Wide (0.2mm))

1	2	3	4	5
---	---	---	---	---

- Accuracy

(Loose <0.1mm) / (Average 0.1-0.25mm) / (Tight>0.25mm)

1	2	3	4	5
---	---	---	---	---

- Surface Finish

(Average-Rough>12.5 um) / (Good-Average 3.2-12.5 um) / (Excellent 0-0.32 um)

1	2	3	4	5
---	---	---	---	---

- Quantity

(One) / (Low2-20) / (Medium 20-25) / (High>50)

1	2	3	4	5
---	---	---	---	---

If you think the terminology is difficult to understand please suggest alternative phrasing.

Answers:

The answers to this question are summarized in Table A-11.

	Users	Rating				
		1	2	3	4	5
Min wall thickness	Average		1	1	1	6
	Advanced			1		3
	All		1	2	1	9
Accuracy	Average		1	1		6
	Advanced		1			3
	All		2	1		9
Surface finish	Average			1	1	5
	Advanced			3		1
	All			4	1	6
Quantity	Average			1	2	5
	Advanced				1	3
	All			1	3	9

Table A-11: Responses to AMDSS Screens Part Q1 (Terminology Section).

Question 2: Material properties screen

The second question asked about the material properties screen shown in Figure A-2. It contained two sections which were: information section and screening method section. .

i. Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

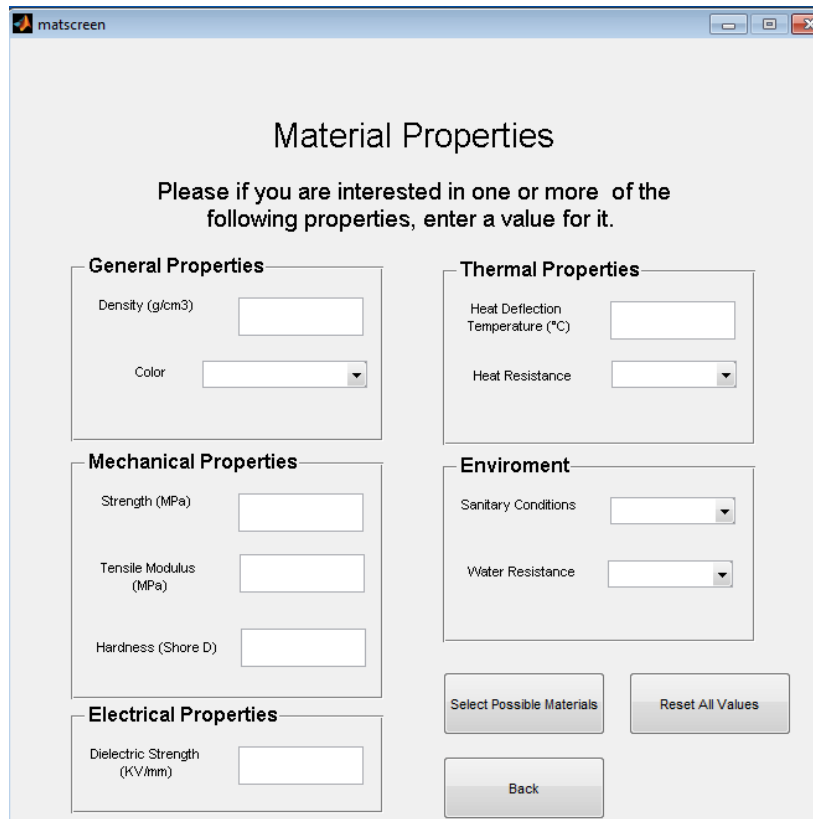


Figure A-2: Material Properties Screen.

Answers:

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-12.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	9/9	Yes	12/13
No	0/4	No	0/9	No	0/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-12: Responses to AMDSS Screens Part Q2a (Information Section).

- b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-13.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	4/9	Yes	4/13
No	3/4	No	5/9	No	8/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-13: Responses to AMDSS Screens Part Q2b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-14.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	3/4	No	9/9	No	12/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-14: Responses to AMDSS Screens Part Q2c (Information Section).

d. Are there any fields that you would add?

Three advanced users said no and the fourth left this question blank. One of them commented to rename sanitary conditions to medical consideration. Another One suggested having alternative units for selections. Three average users said yes and six Average users answered no. The three who answered yes have different comments: one of them suggested adding flexural modulus, another one suggested adding biocompatible, environmental impact, and flexural modulus, the third one suggested adding porous, and hygroscopic (ability of the material to hold water). The answers to this question are summarized in Table A-15.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	3/9	Yes	3/13
No	3/4	No	6/9	No	9/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-15: Responses to AMDSS Part Screens Q2d (Information Section).

ii. Screening Method Section

1- Do you prefer the material screening method to be :

- a. A generalized screening method like by selecting material class (Metals, Plastics, Ceramics, Composites, Wood. .etc)
- b. A properties screening method by giving values to one or more material properties.
- c. I would like to choose every time I make a selection between the two screening methods.

Answers:

The answers to this question are summarized in Table A-16.

Advanced Users		Average Users		All Respondents	
Generalized	2/4	Generalized	3/9	Generalized	5/13
Properties	1/4	Properties	0/9	Properties	1/13
Choose every time	0/4	Choose every time	6/9	Choose every time	6/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-16: Responses to AMDSS Screens Part Q1 (Screening Method Section).

- 2- According to the material properties screening method do you think that it should be based on:
- a. Minimum values.
 - b. Maximum values
 - c. Both

The answers to this question are summarized in Table A-17.

Advanced Users		Average Users		All Respondents	
Min	2/4	Min	2/9	Min	4/13
Max	0/4	Max	0/9	Max	0/13
Both	1/4	Both	5/9	Both	6/13
No Answer	1/4	No Answer	2/9	No Answer	3/13

Table A-17: Responses AMDSS Screens Part Q2 (Screening Method Section).

Question 3: Criteria weighting screen

The third question asked about the criteria weighting screen shown in Figure A-3. It contained one section which is the information section.

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

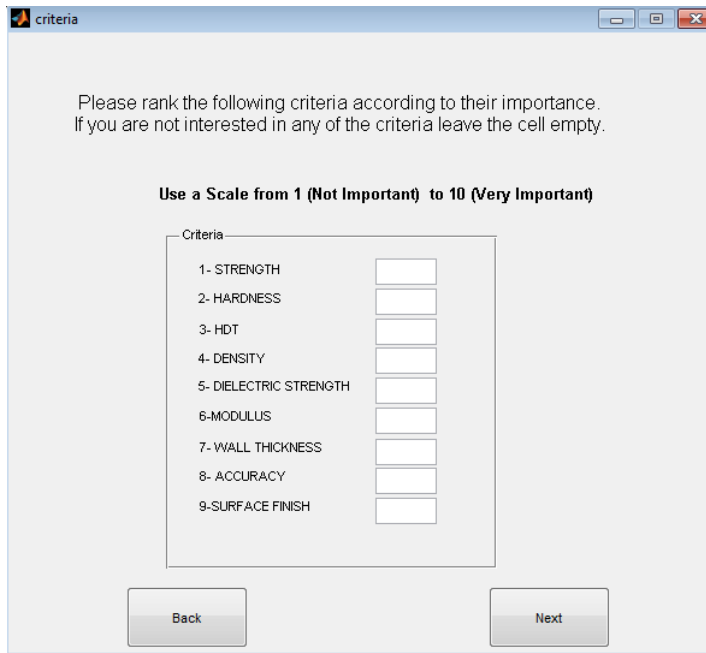


Figure A-3: Criteria Weighting Screen.

Answers:

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-18.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	7/9	Yes	11/13
No	0/4	No	0/9	No	0/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-18: Responses to AMDSS Screens Part Q3a (Information Section).

- b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-19.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	5/9	Yes	5/13
No	3/4	No	2/9	No	5/13
No Answer	1/4	No Answer	2/9	No Answer	3/13

Table A-19: Responses to AMDSS Screens Part Q3b (Information Section).

- c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-20.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	4/4	No	6/9	No	10/13
No Answer	0/4	No Answer	3/9	No Answer	3/13

Table A-20: Responses to AMDSS Screens Part Q3c (Information Section).

d. Are there any fields that you would add?

Two advanced users said yes, and two said no. The first user with positive answer commented to add building time and the second one commented to add elongation and impact strength. Four average users said yes, three said no and two did not answer. The first average user who said yes wanted to add cost and modulus. The second user wanted to add cost of materials. The third one suggested adding relative ranking of indicative cost (high, medium, low) of process material and also to add lead time. Finally the fourth user also suggested adding cost. The answers to this question are summarized in Table A-21.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	4/9	Yes	6/13
No	2/4	No	3/9	No	5/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-21: Responses to AMDSS Screens Part Q3d (Information Section).

Question 4: Final ranking screen

The fourth question asked about the final ranking screen shown in Figure A-4. It consisted of one section which is the scoring results section.

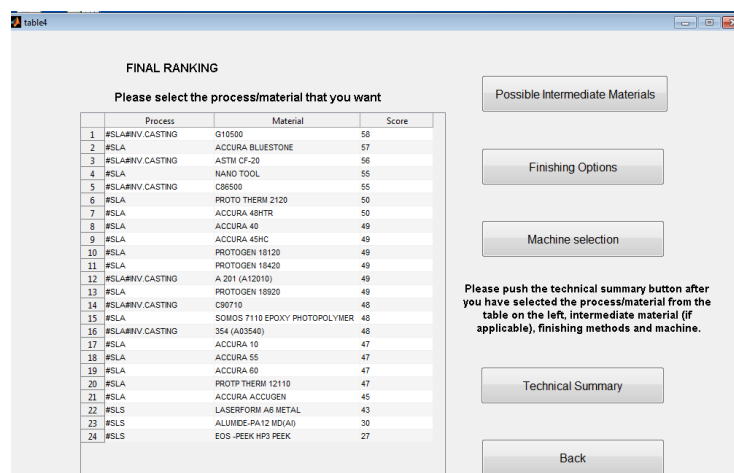


Figure A-4: Final Ranking Screen.

Scoring Results Section

- a. Are the scoring results clear and understandable? If no please comment.
- b. Would you add or remove any information presented?

Answers:

- a. Are the scoring results clear and understandable? If no please comment.

The answers to this question are summarized in Table A-22.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	6/9	Yes	9/13
No	1/4	No	2/9	No	3/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-22: Responses to AMDSS Screens Part Q4a (Scoring Results Section).

- b. Would you add or remove any information presented?

Two advanced users did not want to add or remove anything. The other two, one suggested to add indicating costing and the other one suggested to add info on material such as resin, nylon..etc. Six average users answered yes, one answered no and two left this question blank. The first average user who said yes suggested removing the score. The second one suggested adding a summary of each final entry. The third and fourth user suggested adding cost. The fifth suggested adding colour to this screen. Finally the sixth user suggested showing the score calculation. The answers to this question are summarized in Table A-23.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	6/9	Yes	8/13
No	2/4	No	1/9	No	3/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-23: Responses to AMDSS Screens Part Q4b (Scoring Result Section).

Question 5: Process update screen

The fifth question asked about the process update screen shown in Figure A-5. It contained one section which is the information section.

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Figure A-5: Process Update Screen.

Answers

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-24.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	6/9	Yes	9/13
No	0/4	No	2/9	No	2/13
No Answer	1/4	No Answer	1/9	No Answer	2/13

Table A-24: Responses to AMDSS Screens Part Q5a (Information Section).

b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-25.

Advanced Users		Average Users		All Respondents	
Yes	1/4	Yes	7/9	Yes	8/13
No	2/4	No	1/9	No	3/13
No Answer	1/4	No Answer	1/9	No Answer	2/13

Table A-25: Responses to AMDSS Screens Part Q5b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-26.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	3/4	No	8/9	No	11/13
No Answer	1/4	No Answer	1/9	No Answer	2/13

Table A-26: Responses to AMDSS Screens Part Q5c (Information Section).

d. Are there any fields that you would add?

Two advanced users said yes, one said no and one did not answer this question. The first user who said yes suggested adding process time and the second user suggested adding part volume. Seven average users answered no and two users did not answer this question. The answers to this question are summarized in Table A-27.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	0/9	Yes	2/13
No	1/4	No	7/9	No	8/13
No Answer	1/4	No Answer	2/9	No Answer	2/13

Table A-27: Responses to AMDSS Screens Part Q5d (Information Section).

Question 6: Material update screen

The sixth question asked about the material update screen shown in Figure A-6. It contained one section which is the information section.

Figure A-6: Material Update Screen

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Answers:

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-28.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	6/9	Yes	9/13
No	1/4	No	1/9	No	2/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-28: Responses to AMDSS Screens Part Q6a (Information Section).

b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-29.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	5/9	Yes	5/13
No	4/4	No	3/9	No	7/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-29: Responses to AMDSS Screens Part Q6b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-30.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	4/4	No	8/9	No	12/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-30: Responses to AMDSS Screens Part Q6c (Information Section).

d. Are there any fields that you would add?

Three advanced user said yes and one said no. The first user suggested adding material cost. The second user suggested adding more properties like for example chemical properties. The third user suggested adding speed because different materials can take longer time on the same machine. Three average users said yes, five answered no and one did not answer this question. The first user who said yes suggested adding flexural modulus, the second user suggested adding cost and the third user suggested adding electrical resistance and porosity. The answers to this question are summarized in Table A-31.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	3/9	Yes	3/13
No	3/4	No	5/9	No	8/13
No Answer	1/4	No Answer	1/9	No Answer	2/13

Table A-31: Responses to AMDSS Screens Part Q6d (Information Section).

Question 7: Machine update screen

The seventh question asked about the Machine update screen shown in Figure A-7. It contained one section which is the information section.

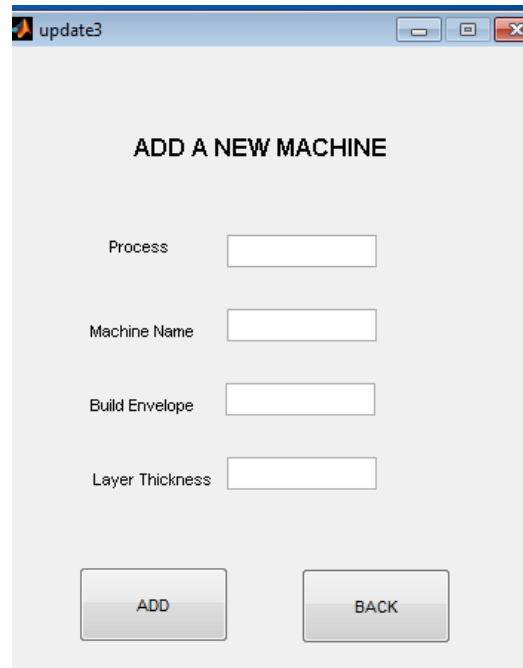


Figure A-7: Machine Update Screen.

Information Section

- Do you think that the information required is appropriate?
- For your application, do you have data for all the presented fields?
- Are there any fields that you would remove?
- Are there any fields that you would add?

Answers:

- Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-32.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	6/9	Yes	10/13
No	0/4	No	2/9	No	2/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-32: Responses to AMDSS Screens Part Q7a (Information Section).

b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-33.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	3/9	Yes	5/13
No	1/4	No	1/9	No	2/13
No Answer	1/4	No Answer	5/9	No Answer	6/13

Table A-33: Responses to AMDSS Screens Part Q7b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-34.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	3/4	No	9/9	No	12/13
No Answer	1/4	No Answer	0/9	No Answer	1/13

Table A-34: Responses to AMDSS Screens Part Q7c (Information Section).

d. Are there any fields that you would add?

Three advanced users said no, and the fourth would like to add beam diameter because this is related to accuracy. One average user answered yes and he would like to add machine availability. Five users answered no and three did not answer. The answers to this question are summarized in Table A-35.

Advanced Users		Average Users		All Respondents	
Yes	1/4	Yes	1/9	Yes	2/13
No	3/4	No	5/9	No	8/13
No Answer	0/4	No Answer	3/9	No Answer	3/13

Table A-35: Responses to AMDSS Screens Part Q7d (Information Section).

Question 8: Finishing options update screen

The eighth question asked about the finishing options update screen shown in Figure A-8. It contained one section which is the information section.

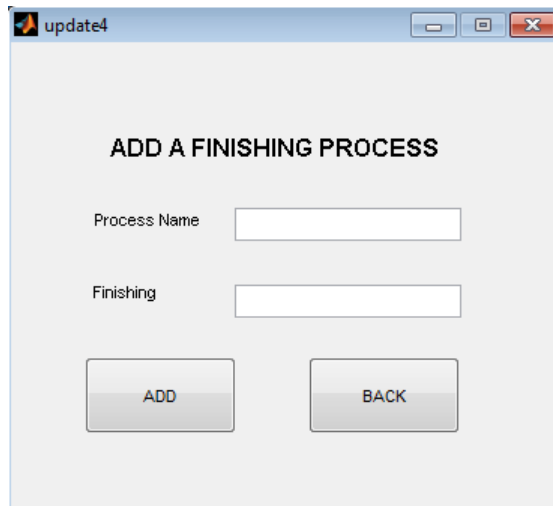


Figure A-8: Finishing Options Update.

Information Section

- a. Do you think that the information required is appropriate?
- b. For your application, do you have data for all the presented fields?
- c. Are there any fields that you would remove?
- d. Are there any fields that you would add?

Answers:

- a. Do you think that the information required is appropriate?

The answers to this question are summarized in Table A-36.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	5/9	Yes	9/13
No	0/4	No	0/9	No	0/13
No Answer	0/4	No Answer	4/9	No Answer	4/13

Table A-36: Responses to AMDSS Screens Part Q8a (Information Section).

- b. For your application, do you have data for all the presented fields?

The answers to this question are summarized in Table A-37.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	4/9	Yes	8/13
No	0/4	No	1/9	No	1/13
No Answer	0/4	No Answer	4/9	No Answer	4/13

Table A-37: Responses to AMDSS Screens Part Q8b (Information Section).

c. Are there any fields that you would remove?

The answers to this question are summarized in Table A-38.

Advanced Users		Average Users		All Respondents	
Yes	0/4	Yes	0/9	Yes	0/13
No	3/4	No	5/9	No	8/13
No Answer	1/4	No Answer	4/9	No Answer	5/13

Table A-38: Responses to AMDSS Screens Part Q8c (Information Section).

d. Are there any fields that you would add?

Two advanced users said yes, and the other two said no. the first user who said yes suggested characterizing processes and quantifying levels of finishing. In addition, adding the time the finishing method could take so this could help in costing. The Second one suggested adding information about the surface the finishing is applied to like: raw metal or paint or lacquer. Furthermore, specifying surface reflectivity (matt, satin, gloss).

Two average users said yes, two said and five users left this question blank. The first user who answered yes commented to add finishing cost, and the second one suggested adding the surface finish level that you get. The answers to this question are summarized in Table A-39.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	2/9	Yes	4/13
No	2/4	No	2/9	No	4/13
No Answer	0/4	No Answer	5/9	No Answer	5/13

Table A-39: Responses to AMDSS Screens Part Q8d (Information Section).

3- General Questions

This part of the questionnaire consisted of twelve questions. The main purpose of this part was to analyze the different aspects of the developed AMDSS and to understand the strength and weakness of it.

Question 1:

The Decision Support System (DSS) has been designed to choose process first than material. Do you think that this is appropriate? Please comment on your answer.

Answers

The answers to this question are summarized in Table A-40.

Advanced Users		Average Users		All Respondents	
Select process first	1/4	Select process first	1/9	Select process first	2/13
Select material first	2/4	Select material first	4/9	Select material first	6/13
Both paths	1/4	Both paths	4/9	Both paths	5/13

Table A-40: Responses to General Questions Part Q.

Question 2:

Did you find the choice of the finishing methods that you want useful? Please comment.

Answers

The first advanced user thought the choice was useful. The second one suggested adding more machinery processes for metal parts. The third one thought choice was useful but quite general and maybe useful for average users but not enough information for advanced users. The fourth one thought that quantification and characterization against conventional surface finishes would be a good option like for example saying that a specific surface finish is like injection plastic surface finish.

Three average users thought that the choice was useful and the other six have different opinions: the first user thought that adding costing and ranking of the finishing options would be a good aspect, the second one thought that more information should be provided like the quality of the surface finish, time and cost, the third one suggested to specify a link surface finishes to applications, the fourth one proposed to add the surface finish level that the user can get from each surface finish option, the fifth one suggested to have more details about the process performance, the sixth one agreed with the idea of the fifth about having

more details and specifications. The answers to this question are summarized in Table A-41.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	3/9	Yes	5/13
No	2/4	No	6/9	No	8/13
No Answer	0/4	No Answer	0/9	No Answer	0/13

Table A-41: Responses to General Questions Part Q2.

Question 3:

Did you find the DSS helpful when you have applied it to your case study for selecting :

- i. The possible processes chains.
- ii. Materials
- iii. Machines
- iv. Finishing methods

Answers

- i. The possible processes chains.

The answers to this question are summarized in Table A-42.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	6/9	Yes	8/13
No	2/4	No	2/9	No	4/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-42: Responses to General Questions Part Q3 (i).

- ii. Materials

The answers to this question are summarized in Table A-43.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	7/9	Yes	10/13
No	1/4	No	1/9	No	2/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-43: Responses to General Questions Part Q3 (ii).

iii. Machines

The answers to this question are summarized in Table A-44.

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	7/9	Yes	9/13
No	2/4	No	1/9	No	3/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-44: Responses to General Questions Part Q3 (iii).

iv. Finishing methods

The answers to this question are summarized in Table A-45

Advanced Users		Average Users		All Respondents	
Yes	2/4	Yes	6/9	Yes	8/13
No	2/4	No	2/9	No	4/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-45: Responses to General Questions Part Q3 (iv).

Question 4:

When the DSS indicates that the part cannot be made using additive manufacturing process, is the information provided clear?

Answers

The answers to this question are summarized in Table A-46.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	6/9	Yes	10/13
No	0/4	No	1/9	No	1/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-46: Responses to General Questions Part Q4.

Question 5:

When the DSS indicates that the part cannot be made using additive manufacturing material, is the information provided clear?

Answers

The answers to this question are summarized in Table A-47.

Advanced Users		Average Users		All Respondents	
Yes	4/4	Yes	6/9	Yes	10/13
No	0/4	No	1/9	No	1/13
No Answer	0/4	No Answer	2/9	No Answer	2/13

Table A-47: Responses to General Questions Part Q5.

Question 6:

Did you find that the DSS provides sufficient information on the ranking and the choices?

Answers

The answers to this question are summarized in Table A-48.

Advanced Users		Average Users		All Respondents	
Yes	3/4	Yes	7/9	Yes	10/13
No	1/4	No	1/9	No	2/13
No Answer	0/4	No Answer	1/9	No Answer	1/13

Table A-48: Responses to General Questions Part Q6.

Question 7:

How important is the ability of updating the process chain, material, finishing and machines in an additive manufacturing DSS?

- a. Not Important
- b. Important
- c. Very Important
- d. Extremely Important

Answers

The answers to this question are summarized in Table A-49.

Advanced Users		Average Users		All Respondents	
Not Important	0/4	Not Important	0/9	Not Important	0/13
Important	1/4	Important	2/9	Important	3/13
Very Important	1/4	Very Important	0/9	Very Important	1/13
Ext. Important	2/4	Ext. Important	4/9	Ext. Important	6/13

Table A-49: Responses to General Questions Part Q7.

Question 8:

What elements do you like to add in the DSS?

Answers

The answers to this question are summarized in Table A-50.

	Advanced	Average	All
Building Time	1	2	3
Costing	2	4	6
Surface finish characterization	1	0	1
Help/Examples/ Welcome screen	1	3	4
More processes+ Materials	1	1	1

Table A-50: Responses to General Questions Part Q8.

Question 9:

What did you like most?

Answers

The answers to this question are summarized in Table A-51.

	Advanced	Average	All
DSS length	1	0	1
Simplicity/easiness of use	2	6	8
Ranking system	1	2	3
Possibility of being updated	0	1	1
Good source of information	0	1	1

Table A-51: Responses to General Questions Part Q9.

Question 10:

What did you dislike most?

Answers

The answers to this question are summarized in Table A-52.

	Advanced	Average	All
No ranges for material properties	1	0	1
Lack of help/guidance	1	7	8
Graphical interface	2	0	2
Lack of ranking score breakdown	0	1	1

Table A-52: Responses to General Questions Part Q10.

Question 11

How do you rate the following elements in the DSS:

Elements	Rating				
	Weak	Fair	Good	Very Good	Excellent
Process selection					
Material selection					
Intermediate material selection					
Finishing selection					
Machines selection					
Process update					
Material update					
Finishing update					
Machine update					
DSS clarity					
DSS length					

Answers

Users select from the rating options: weak, fair, good, very good and excellent. Table A-53 shows both the advanced and average users rating together for the different AMDSS elements. Not all the users have rated all the elements, so some elements do not have thirteen answers.

Elements	Users	Rating				
		Weak	Fair	Good	Very Good	Excellent
Process selection	Average	0	1	5	2	0
	Advanced	0	0	2	1	1
	All	0	1	7	3	1
Material selection	Average	0	1	5	2	1
	Advanced	0	1	1	1	1
	All	0	2	6	3	2
Intermediate material selection	Average	0	1	3	1	1
	Advanced	0	1	1	2	0
	All	0	2	4	3	1
Finishing selection	Average	0	2	4	2	0
	Advanced	1	1	1	1	0
	All	1	3	5	3	0
Machines selection	Average	0	1	3	2	0
	Advanced	0	0	1	3	0
	All	0	1	4	5	0
Process update	Average	0	1	4	1	2
	Advanced	0	1	1	1	1
	All	0	2	5	2	3
Material update	Average	0	1	3	2	1
	Advanced	0	2	2	0	0
	All	0	3	5	2	1
Finishing update	Average	0	2	2	2	1
	Advanced	1	1	1	1	0
	All	1	3	3	3	1
Machine update	Average	0	1	1	2	1
	Advanced	0	0	3	0	1
	All	0	1	4	2	2
AMDSS clarity	Average	0	3	4	1	0
	Advanced	0	0	2	1	1
	All	0	3	6	2	1
AMDSS length	Average	1	0	3	3	0
	Advanced	0	1	1	1	1
	All	1	1	4	4	1

Table A-53: Responses to General Questions Part Q11.

Table A-54 shows the percentage of the user selections dividing the five ratings to two groups which are: 1- weak to fair and 2- good to excellent. The percentage was calculated by dividing on thirteen which is the total number of users. Some users did leave the answer blank.

Elements	Rating				
	Users	Weak to Fair		Good to Excellent	
Process selection	Average	1	11.11%	7	77.78%
	Advanced	0	0.00%	4	100.00%
	All	1	7.69%	11	84.62%
Material selection	Average	1	11.11%	7	77.78%
	Advanced	1	25.00%	3	75.00%
	All	2	15.38%	10	76.92%
Intermediate material selection	Average	1	11.11%	5	55.56%
	Advanced	1	25.00%	3	75.00%
	All	2	15.38%	8	61.54%
Finishing selection	Average	2	22.22%	5	55.56%
	Advanced	1	25.00%	3	75.00%
	All	3	23.08%	8	61.54%
Machines selection	Average	2	22.22%	5	55.56%
	Advanced	0	0.00%	4	100.00%
	All	2	15.38%	9	69.23%
Process update	Average	1	11.11%	7	77.78%
	Advanced	1	25.00%	3	75.00%
	All	2	15.38%	10	76.92%
Material update	Average	1	11.11%	6	66.67%
	Advanced	2	50.00%	2	50.00%
	All	3	23.08%	8	61.54%
Finishing update	Average	2	22.22%	5	55.56%
	Advanced	2	50.00%	2	50.00%
	All	4	30.77%	7	53.85%
Machine update	Average	1	11.11%	4	44.44%
	Advanced	0	0.00%	4	100.00%
	All	1	7.69%	8	61.54%
DSS clarity	Average	3	33.33%	5	55.56%
	Advanced	0	0.00%	4	100.00%
	All	3	23.08%	9	69.23%
DSS length	Average	1	11.11%	6	66.67%
	Advanced	1	25.00%	3	75.00%
	All	2	15.38%	9	69.23%

Table A-54: User Ratings Percentage.

Question 12:

Looking long term, do you think that the best form for this DSS is:

- a. A stand alone application
- b. Online application
- c. A CAD Plug-in.
- d. Other (please state)

Answers

The answers to this question are summarized in Table A-55.

Advanced Users		Average Users		All Respondents	
Stand alone	0	Stand alone	4	Stand alone	4
Online	3	Online	5	Online	8
CAD plug-in	2	CAD plug-in	4	CAD plug-in	6
Other	0	Other	0	Other	0

Table A-55: Responses to General Questions Part Q12.

Appendix B. Second Questionnaire Responses

1- User Profile

Only the users who test the AMDSS for the first time answered the user profile part. The users who have already tested the first version of the AMDSS did not answer this part because they have already filled this information before. Two users have tried the first version so they did not answer and both are classified as advanced users. The remaining four users have answered this part. This part of the questionnaire consists of three questions.

Question1:

How often do you need to select additive manufacturing process or material?

- a. Weekly
- b. Monthly
- c. Sporadically
- d. Other: _____

Answers:

The answers to this question are summarized in Table B-1.

Advanced Users		Average Users		All Respondents	
Weekly	1/1	Weekly	1/3	Weekly	2/4
Monthly	0/1	Monthly	1/3	Monthly	1/4
Sporadically	0/1	Sporadically	1/3	Sporadically	1/4

Table B-1: Responses to User Profile Part Q1.

Question2:

Have you used any knowledge based system for selecting additive process or material before? If yes please name it

Answers:

The answers to this question are summarized in Table B-2.

Advanced Users		Average Users		All Respondents	
Yes	0/1	Yes	0/3	Yes	0/4
No	1/1	No	3/3	No	4/4
No Answer	0/1	No Answer	0/3	No Answer	0/4

Table B-2: Responses to User Profile Part Q2.

Question3:

How do you normally select the following:

- a. Additive manufacturing process
- b. Material
- c. Finishing methods
- d. Machines

Answers:

The answers to this question are summarized in Table B-3.

Advanced Users		Average Users		All Respondents	
Application/ Accuracy	1/1	Application/ Accuracy	0/3	Application/ Accuracy	1/4
Experience/ Asking Experts	0/1	Experience/ Asking Experts	3/3	Experience/ Asking Experts	3/4
No Answer	0/1	No Answer	0/3	No Answer	0/4

Table B-3: Responses to User Profile Part Q3.

2- General Questions

This part of the questionnaire consists of twelve questions. The questions and the answers of the users are described below.

Question1:

Would you like to add any information to any of the AMDSS screens?

Answers:

Two of the advanced users answered this question with yes while the third user answered with no. The first user suggested adding more machines and adding the ability of the selection by engineering materials. There are differences between the

AM materials and engineering materials. For example the ABS used in FDM process is not the same ABS used in injection plastic. He suggested that the system could be able to find the closest material to an engineering material. The second user thought that some simplifications are required for the average users.

Two of the three average users answered this question with no. the third user answered yes and suggested to have a home button in every screen that direct users to the start screen with one click. The answers to this question are summarized in Table B-4.

Advanced Users		Average Users		All Respondents	
Yes	2/3	Yes	1/3	Yes	3/6
No	1/3	No	2/3	No	3/6
No Answer	0/3	No Answer	0/3	No Answer	0/6

Table B-4: Responses to General Questions Part Q1.

Question 2:

Would you like to remove any information to any of the AMDSS screens?

Answers:

The answers to this question are summarized in Table B-5. The user, who answered with yes, suggested removing from the database some SLA materials because the list from his point of view is very exhaustive.

Advanced Users		Average Users		All Respondents	
Yes	1/3	Yes	0/3	Yes	1/6
No	2/3	No	3/3	No	5/6
No Answer	0/3	No Answer	0/3	No Answer	0/6

Table B-5: Responses to General Questions Part Q2.

Question3:

Did you find the AMDSS helpful when you have applied it to your case study for selecting:

- I. The possible process chains.
- II. Materials
- III. Machines

IV. Finishing methods

Answers:

I. The possible process chains.

The answers to this question are summarized in Table B-6.

Advanced Users		Average Users		All Respondents	
Yes	2/3	Yes	2/3	Yes	4/6
No	1/3	No	0/3	No	1/6
No Answer	0/3	No Answer	1/3	No Answer	1/6

Table B-6: Responses to General Questions Part Q3 (I).

II. Materials

The answers to this question are summarized in Table B-7.

Advanced Users		Average Users		All Respondents	
Yes	2/3	Yes	2/3	Yes	4/6
No	0/3	No	0/3	No	0/6
No Answer	1/3	No Answer	1/3	No Answer	2/6

Table B-7: Responses to General Questions Part Q3 (II).

III. Machines

The answers to this question are summarized in Table B-8.

Advanced Users		Average Users		All Respondents	
Yes	2/3	Yes	3/3	Yes	5/6
No	0/3	No	0/3	No	0/6
No Answer	1/3	No Answer	0/3	No Answer	1/6

Table B-8: Responses to General Questions Part Q3 (III).

IV. Finishing methods

The answers to this question are summarized in Table B-9.

Advanced Users		Average Users		All Respondents	
Yes	2/3	Yes	2/3	Yes	4/6
No	0/3	No	0/3	No	0/6
No Answer	1/3	No Answer	1/3	No Answer	2/6

Table B-9: Responses to General Questions Part Q3 (IV).

Question 4:

How important is the ability of updating the process chain, material, finishing and machines to you in an additive manufacturing DSS?

- a. Not Important
- b. Important
- c. Very Important
- d. Extremely Important

Answers:

The answers to this question are summarized in Table B-10.

Advanced Users		Average Users		All Respondents	
Not Important	0/3	Not Important	0/3	Not Important	0/6
Important	1/3	Important	0/3	Important	1/6
Very Important	1/3	Very Important	0/3	Very Important	1/6
Ext. Important	1/3	Ext. Important	3/3	Ext. Important	4/6

Table B-10: Responses to General Questions Part Q4.

Question 5:

What elements do you like to add to the AMDSS?

Answers:

The answers to this question are summarized in Table B-11.

	Advanced	Average	All
Matching Eng. Materials with AM Materials	1/3	0/3	1/6
Costing	1/3	0/3	1/6
Mechanical Properties Variations versus orientation	1/3	0/3	1/6
Nothing to Add	0/3	2/3	2/6
No Answers	0/3	1/3	1/6

Table B-11: Responses to General Questions Part Q5.

Question 6:

What did you like most?

Answers:

The answers to this question are summarized in Table B-12.

	Advanced	Average	All
DSS Improvements	2/3	0/3	2/6
Simplicity	1/3	0/3	1/6
Surface Finish Selection	0/3	1/3	1/6
User Assistance	0/3	1/3	1/6
No Answer	0/3	1/3	1/6

Table B-12: Responses to General Questions Part Q6.

Question 7:

What did you dislike most?

Answers:

The answers to this question are summarized in Table B-13.

	Advanced	Average	All
Nothing	3/3	2/3	5/6
No Answer	0/3	1/3	1/6

Table B-13: Responses to General Questions Part Q7.

Question 8:

How do you rate the following elements in the AMDSS:

Elements	Rating				
Process selection	Weak	Fair	Good	Very Good	Excellent
Material selection	Weak	Fair	Good	Very Good	Excellent
Intermediate material selection	Weak	Fair	Good	Very Good	Excellent
Finishing selection	Weak	Fair	Good	Very Good	Excellent
Machines selection	Weak	Fair	Good	Very Good	Excellent
Process update	Weak	Fair	Good	Very Good	Excellent
Material update	Weak	Fair	Good	Very Good	Excellent
Finishing update	Weak	Fair	Good	Very Good	Excellent
Machine update	Weak	Fair	Good	Very Good	Excellent
DSS clarity	Weak	Fair	Good	Very Good	Excellent
DSS length	Weak	Fair	Good	Very Good	Excellent

Answers:

Elements	Users	Rating				
		Weak	Fair	Good	Very Good	Excellent
Process selection	Average					2
	Advanced				2	1
	All				2	3
Material selection	Average					2
	Advanced				2	1
	All				2	3
Intermediate material selection	Average				1	1
	Advanced				3	
	All				4	1
Finishing selection	Average					2
	Advanced		1	1	1	
	All		1	1	1	2
Machines selection	Average				1	1
	Advanced		1		1	1
	All		1		2	2
Process update	Average				1	1
	Advanced			2	1	
	All			2	2	1
Material update	Average					2
	Advanced			2	1	
	All			2	1	2
Finishing update	Average				1	1
	Advanced			3		
	All			3	1	1
Machine update	Average					2
	Advanced			2	1	
	All			2	1	2
AMDSS clarity	Average				1	1
	Advanced				2	1
	All				3	2
AMDSS length	Average					2
	Advanced			1	2	
	All			1	2	2

Table B-14: Responses to General Questions Part Q8.

Users select from the rating options: weak, fair, good, very good and excellent. Table B-14 shows both the advanced and average users rating for the different AMDSS elements. One average user has left this question blank.

Table B-15 shows the percentage of the user selections dividing the five ratings to two groups which are: 1- weak to fair and 2- good to excellent. The percentage was calculated by dividing on six which is the total number of users.

Elements	Rating				
	Users	Weak to Fair		Good to Excellent	
Process selection	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Material selection	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Intermediate material selection	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Finishing selection	Average			2	66.67%
	Advanced	1	33.33%	2	66.67%
	All	1	16.67%	4	66.67%
Machines selection	Average			2	66.67%
	Advanced	1	33.33%	2	66.67%
	All	1	16.67%	4	66.67%
Process update	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Material update	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Finishing update	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
Machine update	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
DSS clarity	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%
DSS length	Average			2	66.67%
	Advanced			3	100%
	All			5	83.33%

Table B-15: User Ratings Percentage

Question 9:

Looking long term, do you think that the best form for a DSS of this type is:

- a. A stand alone application
- b. Online application
- c. A CAD Plug-in.
- d. Other (please state)

Answers:

The answers to this question are summarized in Table B-16.

Advanced Users		Average Users		All Respondents	
Stand alone	2	Stand alone	0	Stand alone	2
Online	2	Online	2	Online	4
CAD plug-in	2	CAD plug-in	2	CAD plug-in	4
Other	0	Other	0	Other	0

Table B-16: Responses to General Questions Part Q9

Question 10:

If you have used the first version of this system, how do you compare the 1st version to the 2nd version with regard to:

I. The process selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

II. The material selection:

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

III. Finishing selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

IV. Machine selection

- a- Same
- b- 2nd version better
- c- 1st version better

Comment:

Answers:

The answers to this question are summarized in Table B-17.

	Same	2 nd version better	1 st version better
Process Selection		2	
Material Selection		2	
Finishing Selection	1	1	
Machine Selection	1	1	

Table B-17: Responses to General Questions Part Q10

Question 11:

Please comment on the following capabilities of the AMDSS:

- I. Selecting material first or process first.
- II. Selecting by material class or by material properties.
- III. Determining minimum and maximum values of the material properties.
- IV. Helping on the finishing strategies selection.

Answers:

I. Selecting material first or process first.

The answers to this question are summarized in Table B-18.

Advanced Users		Average Users		All Respondents	
Good Improvement	2/3	Good Improvement	1/3	Good Improvement	3/6
Essential Option	1/3	Essential Option	0/3	Essential Option	1/6
Very Useful	0/3	Very Useful	1/3	Very Useful	1/6
No Answer	0/3	No Answer	1/3	No Answer	1/6

Table B-18: Responses to General Questions Part Q11 (I)

II. Selecting by material class or by material properties.

The answers to this question are summarized in Table B-19.

Advanced Users		Average Users		All Respondents	
Good Improvement	2/3	Good Improvement	1/3	Good Improvement	3/6
Essential Option	1/3	Essential Option	0/3	Essential Option	1/6
Very Useful	0/3	Very Useful	1/3	Very Useful	1/6
No Answer	0/3	No Answer	1/3	No Answer	1/6

Table B-19: Responses to General Questions Part Q11 (II).

III. Determining minimum and maximum values of the material properties.

The answers to this question are summarized in Table B-20.

Advanced Users		Average Users		All Respondents	
Good Improvement	2/3	Good Improvement	0/3	Good Improvement	2/6
Essential Option	1/3	Essential Option	0/3	Essential Option	1/6
Very Useful	0/3	Very Useful	2/3	Very Useful	2/6
No Answer	0/3	No Answer	1/3	No Answer	1/6

Table B-20: Responses to General Questions Part Q11 (III).

IV. Helping on the finishing strategies selection.

The answers to this question are summarized in Table B-21.

Advanced Users		Average Users		All Respondents	
Good Improvement	1/3	Good Improvement	0/3	Good Improvement	1/6
Essential Option	1/3	Essential Option	0/3	Essential Option	1/6
Very Useful	0/3	Very Useful	2/3	Very Useful	2/6
No Answer	1/3	No Answer	1/3	No Answer	2/6

Table B-21: Responses to General Questions Part Q11 (IV).

Question 12:

Do you have any suggestions for improving the AMDSS?

Answers:

The answers to this question are summarized in Table B-22.

Advanced Users		Average Users		All Respondents	
Add Material Class	1/3	Add Material Class	0/3	Add Material Class	1/6
Appearance	0/3	Appearance	1/3	Appearance	1/6
No Answer	2/3	No Answer	1/3	No Answer	3/6
Nothing	0/3	Nothing	1/3	Nothing	1/6

Table B-22: Responses to General Questions Part Q12.

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