Aalto University

School of Science

Degree Programme in Information Networks

Process and Web Application Development of Medical Applications of Additive Manufacturing

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Master's Thesis

Espoo, December 27th, 2011

Supervisor: Professor Eila Järvenpää

Instructor: Jukka Tuomi (Lic. Tech.)

Aalto University School of Science	ABSTRACT OF THE MASTER'S THESIS

Author: Juho Vehviläinen	
Title: Process and Web Application Development of Medical Applications of Additive Manufacturing	
Title in Finnish: Pikavalmistuksen lääketieteellisten sovellusten prosessien ja verkkosovelluksen kehittäminen	
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Supervisor: Professor Eila Järvenpää	Instructor: Jukka Tuomi (Lic. Tech.)

The objective of this Master's Thesis was to develop a matrix framework and an online platform for documenting and planning medical applications of additive manufacturing (MAAM) cases. The study was motivated by the fact that the MAAM field is lacking a classification standard and a process model which depict the design and manufacturing process of medical applications of additive manufacturing. For this particular reason, the goal and motivation of this research work was to develop a web tool which enables professionals to collaborate meaningfully on this complex and multidisciplinary subject.

This research applied constructive research method. It is a research approach in which a practical solution to a concrete problem is produced. MAAM matrix was developed through literary research, interviews and team meetings with medical and additive manufacturing professionals. Emphasis in the development process was put in discovering all the necessary process steps and their subcategories that should be depicted in the matrix. The online platform development included building a viable general purpose web server and using Drupal content management system and PHP programming language to create a dynamic website.

The result of the research concluded a dynamic website where users can view and document MAAM cases using the designed matrix framework, get information about MAAM and communicate and collaborate with other professionals in the field. The validity of the solution was tested with eight different patient cases for which the matrix and the documenting tools were more than sufficient. The website was presented to both medical and additive manufacturing professionals who saw the solution to be clear and illustrative, predicting a positive future for the matrix solution and the website among professionals in the MAAM field.

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Tämän diplomityön tavoitteena oli kehittää luokittelu ja prosessimatriisi sekä verkkosovellus pikavalmistuksen lääketieteellisille sovelluksille. Pikavalmistuksen lääketieteellisille sovelluksille ei ole aikaisemmin ollut kunnollista luokittelustandardia ja prosessikuvausta, jolla voitaisiin havainnollisesti kuvata ja dokumentoida eri tyyppisiä potilashoitotapauksia. Tämä on hankaloittanut potilastapausten dokumentointia ja niistä keskustelua toimialan sisällä. Tästä johtuen tämän työn motivaationa ja tavoitteena oli kehittää verkkosovellus, jonka avulla alan asiantuntijat voivat käydä johdonmukaista diskurssia tästä monivaiheisesta ja monitieteisestä prosessista.

Diplomityö toteutettiin konstruktiivisena tutkimuksena, jossa tutkimusongelmaan kehitettiin käytännöllinen ratkaisu. Kirjallisuustutkimuksen, haastattelujen ja ryhmätapaamisten pohjalta kehitettiin lopullinen pikavalmistuksen lääketieteellisten sovellusten matriisi, jossa on yhdistettynä sekä luokittelut että niiden prosessikuvaukset. Matriisikehityksen jälkeen rakennettiin yleiskäyttöinen palvelin ja verkkosovellus toteutettiin Drupal - sisällönhallintajärjestelmällä ja PHP - ohjelmointikielellä.

Tutkimuksen tuloksena syntyi dynaamiset verkkosivut, jossa käyttäjät voivat dokumentoida pikavalmistuksen lääketieteellisiä sovelluksia käyttäen matriisiviitekehystä, saada informaatiota aiheesta ja käydä keskustelua muiden alan asiantuntijoiden kanssa. Matriisin soveltuvuutta testattiin kahdeksalla eri hoitotapauksella, joihin se soveltui ongelmitta. Verkkosivujen käyttöä havainnollistettiin sekä lääketieteen että pikavalmistuksen asiantuntijoille, jotka pitivät toteutustapaa selkeänä ja havainnollisena ennustaen sivustolle hyvää vastaanottoa alan asiantuntijoiden piirissä.

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Foreword

When I was presented the opportunity to work on a project that combines technological (web development & additive manufacturing technologies), medical (medical applications) and work psychological (interdisciplinary collaboration) aspects I was intrigued by the challenge. It was somehow fitting to have a research topic that covered many disciplines because my studies as a whole had been a combination of many different subjects.

In the beginning, little I knew about the challenges that I was going to face during the research. On the other hand, I also did not realize how Information Networks Degree Programme had prepared me for this journey. The basic idea of the degree program is to educate students to work as a link between the end users and the developers of high technology. That is exactly what the long term goal of this research is - to build groundwork for better collaboration between engineers and medical professionals.

I would like to thank my project team, my supervisor Eila Järvenpää, my instructor Jukka Tuomi and everyone who contributed to the research process assisting me to get this far. Also, a special mention goes to those many, faceless user names in Drupal forums that answered my endless questions during web development phase. Open source community, thank you for your support.

Espoo, December 2011

Juho Vehviläinen

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1 Introduction

1.1 Background and Motivation

Additive manufacturing (AM) refers to a group of processes which are involved in joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. AM is most commonly used for modeling, prototyping, tooling and short-run production applications because it is a fast, reliable and in most cases relatively inexpensive way to manufacture tailored, geometrically complex 3D objects. Plastics, metals, ceramics and composite materials can be used in AM and as the technology develops, more and more new materials with different characteristics are introduced to AM processes. (Wohlers 2010)

Since additive manufacturing has been in use it has been called with many names such as rapid manufacturing, solid freeform fabrication, freeform fabrication and laminated manufacturing. The term additive manufacturing (AM) was recently coined in American Society for Testing and Materials (ASTM) international standard as a standard term so the term AM will be used in this thesis. Nevertheless, the reader should be aware that terms listed above might come up especially in older publications.

Many different industries have benefited from using AM in their product development phases and when manufacturing a short series of customized products. AM technologies have been used in manufacturing of digital cameras, mobile phones, interior trim for automobiles, engine parts, assemblies and parts for airplanes, medical and dental implants just to name a few. (Wohlers 2010)

Medical imaging technologies (CT, CBCT, MRI, etc.) have also developed rapidly and the cost of imaging has dropped. For example, in the past years in order to create a model of a jawbone the patient was required to pay €600 - €900 for a Computed Tomography (CT) scan which can be done for €100 - €200 today using Cone Beam CT (CBCT) technology. (Wohlers 2010) As the price of imaging has dropped it has become more feasible to use AM to manufacture and develop applications for medical purposes such as real size cranial models for surgical planning, inert implants and prostheses and specially designed medical tools.

This thesis is done for Integrated Design and Manufacturing (IDM) group, which is a research group BIT Research Center at Aalto University. The research group is working in the areas of R&D systems and process development aiming to produce competitive solutions for manufacturing industry. Additive manufacturing, and technologies related to it, are an essential part of their work. IDM group had a project called Bioman II[1] which was aimed to research and develop medical applications of additive manufacturing. The project plan was to research and develop new kinds of treatment processes that additive manufacturing enables and during the research IDM group managed to create the first digitally designed and additive manufactured personal implant in Finland. See the implant in Figure 1 and description below.

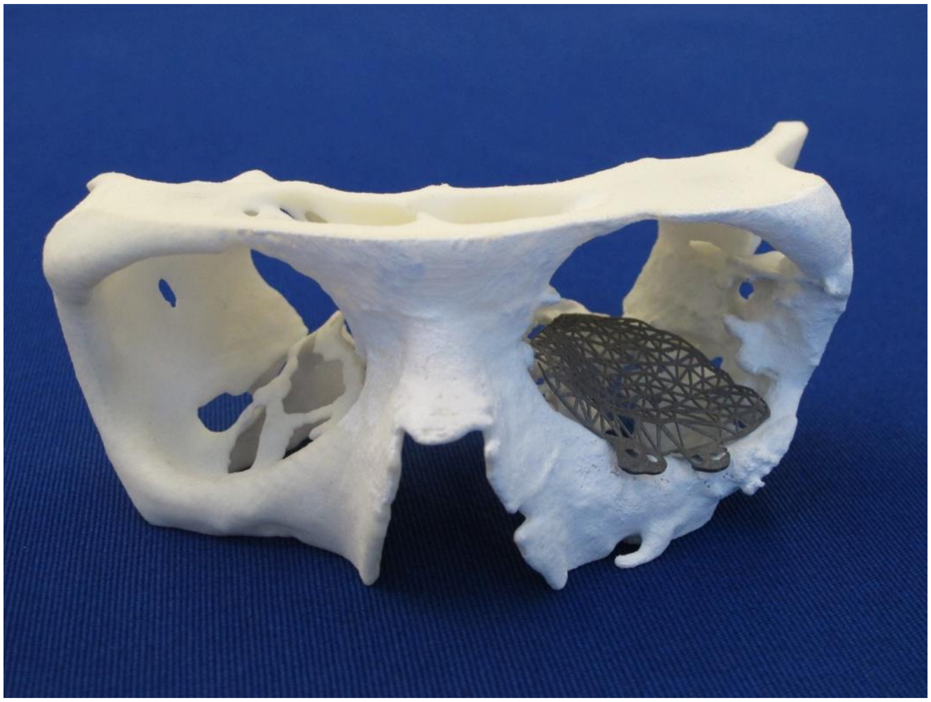

Figure 1: A Rapid manufactured skull model and personal orbital reconstruction implant

AM has been applied to a wide range of medical areas already, including cranio-maxillofacial and dental surgery, orthopedics, orthosis and tissue engineering. AM is a good technology for

[1] Bioman II, Tekes (283/31/07), 2010-2012

medical applications because it allows the development of custom made (personalized) medical applications based on patient data to meet specific clinical and geometrical constraints. It especially shows its benefits in complex surgeries where preoperative planning of the surgery becomes more important. When implants and surgical aid tools can be made accurately preoperatively the surgeon's skills are enhanced; the precision, safety and speed of surgery are increased; and finally the complexity of surgery is reduced. (Hieu et al 2005)

Even though implants, prostheses, tools and other medical applications have already been manufactured for some years using AM, it is still a relatively new area of production. The production process has many steps which need different kind expertise and many actors are involved in the process. It is truly a multidisciplinary field, which draws resources from medical imaging, design and manufacturing, tooling, biomaterials, IT-technology and bioengineering. (Marciniec & Miechowicz 2004) (Abbaszadeh et al. 2010)

One essential part of the thesis is to come up with a process model (a matrix) which depicts all the necessary steps in manufacturing of medical applications of additive manufacturing (MAAM from now on). At the moment communication between medical professionals and AM professionals is undeveloped which limits the possibilities of using AM for medical applications. One main goal of the process model is to increase communication between the medical and AM communities and thus enable better collaboration. Taking this to consideration we can say that there is a clear need for this kind of process model so the process can be mapped and made to function more efficiently. AM process already in itself needs a lot of different expertise from 3D-CAD modeling to material technology, and when we add medical dimension it becomes a truly complex, interdisciplinary process so efficient communication and collaboration is needed. Also, when additive manufacturing becomes more popular in medical applications this process model works as a tool to recognize which kind of processes are involved in different cases and it can help doctors and other actors to realize more clearly the potential of MAAM.

1.2 Research Objectives

The aim of this study is to develop a process model that depicts MAAM manufacturing process and to develop a web-based tool based on this model. The web-based tool works as structured process model which depicts the manufacturing process as a whole and can be used to browse through different MAAM cases. The web interface is connected to a database that has metadata stored about different cases. The application needs to be constructed in a way that enables further development in the future.

IDM group created a quite large database of MAAM related articles during Bioman[2] and Bioman II[1] projects which will be a great starting point for the system. One task during the thesis work is to update that database with new material that comes across and eventually upload all that information to the new database. Also a separate section for IDM group's articles will be created.

	Medical Imaging	3D-CAD Modeling	Additive Manufacturing	Clinical Application
Preoperative				
Inert Implants				
Instruments				
Postoperative				
Biomanufacturing				

Figure 2: Medical applications of rapid prototyping process matrix

Figure 2 above gives an overall picture of the process matrix at the beginning stage of the research. Based on article Medical Applications of Rapid Prototyping – From Applications to Classification by Tuomi et al. (2009) there are five different groups that can be distinguished: 1) Models for preoperative planning, education and training; 2) Inert Implants; 3) Tools, instruments and parts for medical devices; 4) Medical aids, supportive guides, splints and prostheses; 5) Biomanufacturing. These five groups are depicted on the Y-axis. The X-axis

[1] Bioman II, Tekes (283/31/07), 2010-2012

[2] Bioman, Tekes (103/31/05), 2005-2006.

depicts different phases and technologies in the manufacturing process. The thesis concentrates to develop the both the Y- axis and X-axis. Most of the work will be in the process development (X-axis) where the process steps will be taken into closer examination. All the columns in the X-axis are broken down to subcategories and clearer classification of the processes and parameters involved is depicted. This brings us to the main research question of the thesis.

The main ***theoretical research question*** is: *What are the critical stages, technologies and attributes in the process that should be depicted?*

The main ***practical research question*** is: *What are the best suitable tools for creating a dynamic website for medical applications of additive manufacturing?*

1.3 Scope of the Research

There are certain limitations to this research. During this thesis project a classification matrix and a dynamic website will be developed. The website will include most important functionalities that are case and article search, easy case and article input, defined user roles and collaboration capabilities. Future developments can include case evaluations and tools for generating guidelines or best practices for different case types according to case data available. These applications or tools are not in the scope of this research but they still need to be taken into consideration in the planning phase to ensure that the website can manage such developments. Practically this should not produce any problems but it means that the concept (actual process model) should to be more or less fully developed until web application development can begin.

1.4 Research Methods

1.4.1 Constructive Research

This thesis applies constructive research approach which basically means a study in which an innovative solution to a real-world problem is produced. In this case the problem is that the production process of MAAM is not very clear and should be depicted explicitly in order to be able to develop it. It is a real-world problem for which a real-world solution, such as a process model and a web application, can be developed. Figure 3 shows the elements of constructive research.

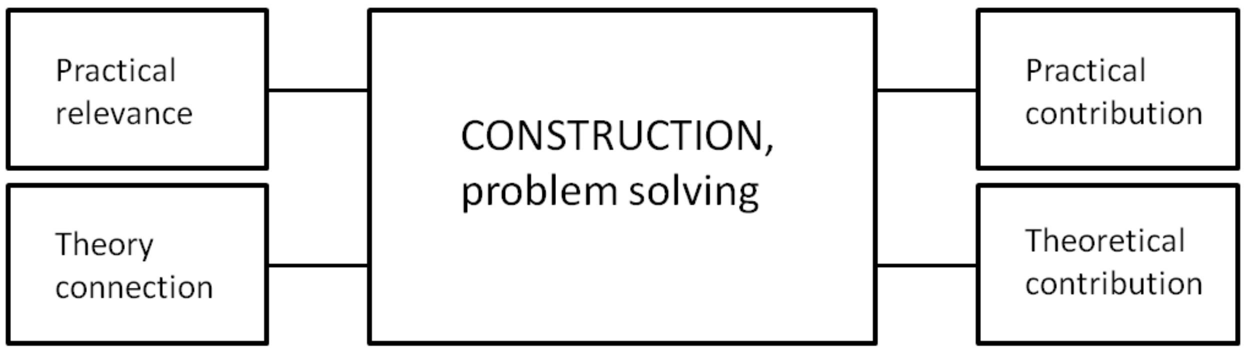

Figure 3: Elements of constructive research (Kasanen et al. 1993)

This research emphasizes more practical relevance and practical contribution compared to the theoretical side. This comes from the fact that the outcome of this research is a web based tool which is designed to help documenting and the manufacturing process of MAAM. Nevertheless, the research still has a theory connection and theoretical contribution which is the development of the classification groups introduced in article by Tuomi et al. (2009) and the development of processes connected to them.

The information about different technologies in the process is also quite scattered. Combining and bridging that information together will not only help to depict the process, but it also helps to bring forth MAAM as a research area.

The constructive approach can be divided into six phases (Kasanen et al 1993):

1. Find a practically relevant problem which also has research potential.
2. Obtain a general and comprehensive understanding of the topic.

3. Innovate, i.e., construct a solution idea.
4. Demonstrate that the solution works.
5. Show the theoretical connections and the research contribution of the solution concept.
6. Examine the scope of applicability of the solution.

This research implements all six phases. A practical problem is to develop a process model and web based tool to enhance knowledge of MAAM processes (1). General understanding of the topic is obtained with literature review of additive manufacturing technologies, medical imaging technologies, 3D-CAD and medical application specific case studies and articles (2). After literature review is complete a process model and web application is produced (3). Different case studies are put to the system and test subjects test and evaluate its functionalities (4). Theory connection is to previous studies of MAAM classifications/groups (5). The scope of applicability will be examined in results and discussions chapter (6).

1.5 Structure of the Thesis

The thesis begins with an Introduction (Chapter I) to background and motivation of the study and defines the objectives, scope, limitations and research methods used.

The research continues to examine Theoretical Background (chapter II) which includes many different areas. In order to be able to construct a process model one needs to understand all the technologies and steps involved in the process. For that I need to familiarize myself with additive manufacturing technologies, imaging technologies and medical applications that are manufactured or can potentially be manufactured using additive manufacturing. After that the chapter discusses theory behind dynamic web application which lays a solid groundwork for creating efficient databases and web applications with high usability.

Empirical Study (chapter III) in this case means web application development. Process model should be done prior to this stage so most of the time would be allocated for writing code and testing the application.

After coding and testing is completed it is time to test the validity of the solution with users. Validation & Results (chapter IV) chapter discusses user experiences and examines how well the application meets its requirements. After user testing some further web development is required and the basic functions for a collaborative site are constructed. This will be the starting point for all future developments of the site. This chapter also discusses different medical application cases in the system. Different professionals globally who have experiences in medical applications of additive manufacturing will be contacted in hopes that they will be willing to contribute their case studies to the system. This would bring a bigger collection of cases, thus more substance, to the system. Documentation about coding and best practices will also be written down which can be used as a reference point for future development.

Conclusion & Discussion (chapter V) is the last chapter of the research. This chapter should sum up all the findings and evaluate the research as a whole.

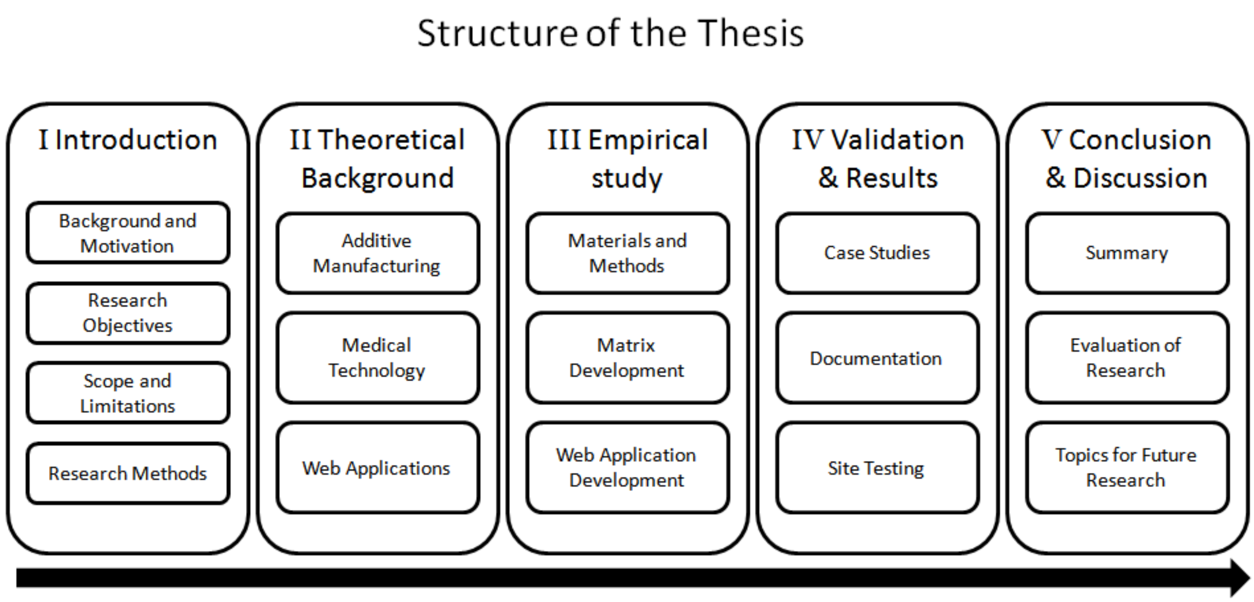

Figure 4: Structure of the Thesis

2 Theoretical Background

Theoretical background chapter builds groundwork for the process development part and web application development of the research. Basic idea of the additive manufacturing technology and related processes are introduced and a medical application viewpoint is carried through the theoretical research. This chapter will give the reader basic knowledge to 3D-CAD modeling, additive manufacturing and medical imaging which are the basic parts of MAAM process. Web server and web application development is also examined.

2.1 Additive Manufacturing in Medical Context

The development in modern imaging, computer aided design and additive manufacturing technologies have made it possible to produce geometrically accurate anatomical models. Medical applications of additive manufacturing have an increasing trend which makes the future of AM very interesting in medical context. The applications may include design, development, and manufacturing of medical models, instrumentation and medical devices, as well as implants, prostheses and scaffolds for bioengineering. (Abbaszadeh et al. 2010)

In recent years, the applications of AM technology in medical area have increased tremendously and an entire new field called medical rapid prototyping (MRP) has emerged. This term has been quite widely used but it can also be a bit misleading. There are not really any specific techniques designed for making medically specific models. The models are always applications of certain AM technique, which is of course used in other industries as well, which makes the term medical applications of additive manufacturing (MAAM) more accurate description. The vocabulary will most likely develop in coming years and some terms will be coined but to clarify this thesis the term MAAM will be used, even though many of the sources will have medical rapid manufacturing, or alike, in their publications.

MAAM (MRP formerly) has mostly meant additive manufacturing of dimensionally accurate 3D physical models of human anatomy derived from medical image data. These models have been most commonly used in preoperative planning of surgeries. “The term medical model stands for a physical reproduction of tissues, models of prostheses, implants and the other auxiliary equipment useful for planning and performing surgical treatments, for training and improving medical attendance and rehabilitation.” (Marciniec & Miechowicz 2004) This physical model can enhance interpretation, visual and physical evaluation, communication between the doctor and the patient and aid in the rehearsal and planning of the surgical steps before a surgical operation is carried out. Why AM is such a good technique for producing medical models is its geometrical accuracy, cost and delivery time. These models could not be cost and time efficiently made using traditional manufacturing methods. (Marciniec & Miechowicz 2004) (Abbaszadeh et al. 2010)

A new classification of MAAM includes a lot more than preoperative models but that will be more thoroughly discussed in Chapter 3.2.1 Classifications. Next chapters will introduce all the basic functions that are needed in MAAM process.

2.2 Medical Imaging Technology

In order to have good production quality using additive manufacturing the quality of medical imaging of bone structures, or any structure for that matter, needs to be high quality. For replicating bone structure X-*Computed tomography* (CT) is the method of choice. Another technique used in the medical field is Cone-Beam Computed Tomography (CBCT). Magnetic Resonance Imaging is the third most popular imaging technique for medical modeling, although this technique is less useful for bone imaging compared to soft-tissue modeling. (Wohlers 2010)

Computed Tomography (CT)

“X-Ray Computed Tomography is an imaging modality that produces cross-sectional images representing the X-ray attenuation properties of the body.” (Suetens 2002) X-rays are produced by an X-ray tube and detected and measured by an X-ray detector after X-rays have passed through and attenuated by patient’s body. The X-ray source and detector pair rotate 360 degrees about the subject and the intersection of the beams provides the needed information to calculate that point in space. After mapping all of the beam intersection a volume is reconstructed. This image reconstruction is accomplished mathematically by back projecting attenuation measurements, producing a cross-sectional map of X-ray attenuation, which practically depicts tissue density. 3D-image datasets are constructed by stacking a series of cross-sectional images together. (Wohlers 2010)

Cone-Beam Computed Tomography (CBCT)

Cone-Beam Computed Tomography (CBCT) has the same principle as traditional CT but instead of single, thin X-ray beam making one revolution per image slice, CBCT uses a larger, diverging X-ray beam a shape of a cone. This enables CBCT technique to acquire a single image dataset from one revolution of the source-detector pair which has benefits in reduced radiation exposure to the patient. CBCT is getting more popular in clinical use (especially in dental, ear, nose, and throat cases) for its ease of scanning and for its practical small size compared to traditional CT devices. Disadvantage of CBCT is poorer contrast resolution compared to traditional CT, making segmentation more difficult. (Wohlers 2010)

Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) basically measures a magnetic property of tissue. It is based on the principle of nuclear magnetic resonance and employs strong magnetic fields and radio waves. In strong primary magnetic field hydrogen protons in water molecules become aligned. After alignment radio waves at specific frequency are introduced to perturb protons from their alignment within the magnetic field. After removing the radio waves, protons return to their alignment at different rates and emit an echo signal that can be measured. Return rates are different depending on tissue type and echo signal used to determine relaxation times, which is the time required for hydrogen nuclei to return to their alignment in the magnetic field, which in turn is used to reconstruct cross-sectional images. MRI is mainly used for soft tissue imaging, because it does not image bone well but has an excellent soft tissue contrast. (Suetens 2002) (Wohlers 2010)

2.3 3D Computer-aided Design

Computer-aided design (CAD) means the use of computer technology in the process of design and design documentation. The main use of CAD systems is detailed engineering of 3D and 2D objects which usually are physical components for bigger assemblies. In addition, it is also used throughout the engineering process from conceptual design and layout of products to definition of manufacturing methods of components. (Laakko et al. 1998) (Farin, Hoshcek & Kim 2002)

From medical application perspective, 3D CAD modeling is very convenient tool for modeling human anatomy or designing prosthesis and implants with the help of CT image data.

Today's CAD systems have reached a high level of sophistication. It is possible to have very specific, real-time, 3-dimensional visualizations of products. A product and its geometrical specifications can be designed in CAD, which is the first obvious use of CAD, but CAD environments often involve more than just shapes of objects. The output of CAD usually has information about materials, processes, dimensions, tolerances and all other application relevant information. (Farin, Hoshcek & Kim 2002)

CAD technologies have become increasingly important in design and manufacturing because of its benefits in lower product development costs and greatly shortened design cycle. It enables designers to develop the entire concept on the on the computer, make quick adjustments and save it for future editing which saves time and money. (Farin, Hoshcek & Kim 2002)

2.4 Additive Manufacturing

The basic principle of additive manufacturing is that a model, which is generated using three-dimensional Computer Aided Design (3D CAD) system, can be fabricated without the need for tools, handwork and process planning. This may not be reality in every case but generally additive manufacturing certainly simplifies the process of producing complex 3D structures directly from CAD data. Other manufacturing techniques require careful planning and analysis of the part geometry in order to decide which tools should be used to fabricate different features of the piece. Additive manufacturing in comparison needs only some basic dimensional details, small amount of knowledge about the machine and used materials. (Gibson, Rosen & Stucker 2010)

Figure 5 shows the idea of additive manufacturing. The cup is made by adding material in layers; each layer is a thin cross-section of the part that is derived from the virtual CAD model. Layer thickness obviously affects the quality and accuracy of the part; the thinner the layers are the smoother is the surface on the side of the cup. Different AM techniques have different layer thickness qualities but generally machines are able to produce very thin layers. For example, generally selective laser sintering (SLS) parts are made of approximately 0.1 mm layer thickness. (Gibson, Rosen & Stucker 2010)

Figure 5: Image of a teacup using different layer thicknesses (Gibson, Rosen & Stucker 2010)

Additive manufacturing involves a number of steps before a 3D CAD model turns into a physical object. Figure 6 shows generative process steps in additive manufacturing process. [1] It starts with a virtual 3D CAD model which has all the geometric information about the part. [2] This is converted to STL (Stereolithography file format) file which has become de facto standard file format in the industry. STL is the format that AM machines understand. [3] STL file is transferred to AM machine and some general manipulation to the file can be made. [4] Before building the part some settings need to be set up, such as material constraints, layer thickness, energy source and so on. [5] Building process is mainly automatic and does not need supervision in most cases. [6] Part removal from the machine. [7] After the part is built, some parts may require additional cleaning and removal of supporting structures. This phase sometimes requires experienced manual manipulation. [8] At this point parts are usually ready for to be used. (Gibson, Rosen & Stucker 2010) In some cases, like in medical applications, additional surface treatment might be needed. These surface treatments can include coating or sterilization.

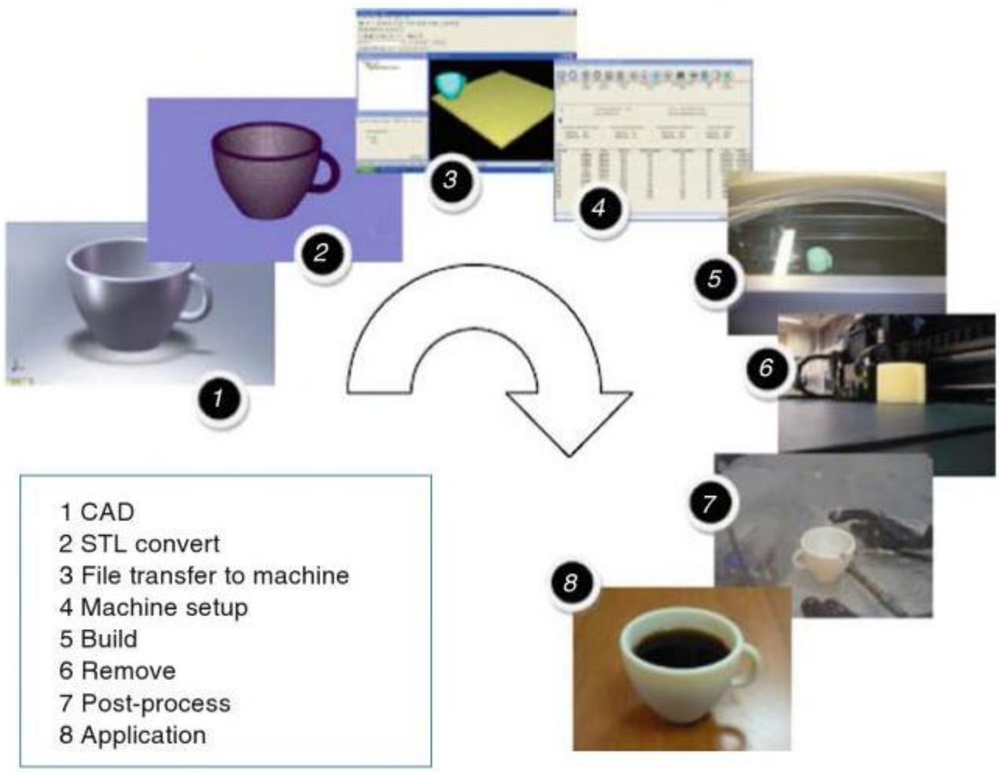

Figure 6: Generic AM process from CAD to physical part (Gibson, Rosen & Stucker 2010)

In medical context, additive manufacturing is already applied in such fields as traumatology, maxillofacial surgery, craniofacial surgery, prosthetics and orthodontics. Some example cases include cranial and craniofacial reconstructions, the treatment of bone and joint deformities, pelvis damage, limb malformations and vertebral injuries. (Marciniec & Miechowicz 2004)

Additive manufacturing techniques are not very widely used in medical applications nowadays but it is expected that this will change in the near future. In the next section some of the most common AM methods that are used in medical applications are presented.

2.4.1 Additive Manufacturing Techniques

This chapter gives a brief introduction to some common AM technologies that are used in medical cases.

Selective Laser Sintering (SLS)

Selective laser Sintering (SLS) is quite common additive manufacturing technique. SLS is a technique which creates three-dimensional solid objects by selectively fusing powder material with laser, turning the powder material into solid objects. (Saleh & Dalgarno 2010)

How SLS precisely works is that the material is preheated to a temperature just slightly below its melting point. After that the laser beam traces the cross-section on the powder surface and heat ups the powder to the sintering temperature. This way the powder that is scanned is bonded. The powder which is not scanned will remain in place to serve as a support for the next layer of powder. After the laser has completed a layer of the cross-section, the roller/sweeper levels another layer of powder over the sintered one. (Yan & Gu 1996)

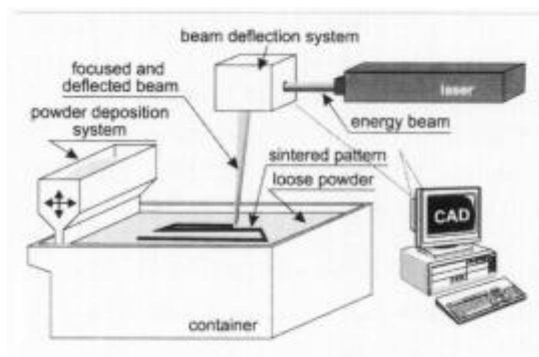

Figure 7: Schematic overview of SLS process (Kruth et al. 2003)

A wide range of materials can be used in SLS process including polycarbonate, polyvinyl chloride (PVC), acrylonirile butadiene stryrene (ABS), nylon, resin, polyester, polypropane and polyurethane. Theoretically, any thermoplastic material which is suitably powdered can be employed. This includes powdered metals, low-melting alloys and ceramic materials. In medical practice SLS is especially suitable for orthopedic use. (Yan & Gu 1996) (Marciniec & Miechowicz 2004)

3D Printing

3D printing (3DP) technology was originally developed at Massachusetts Institute of Technology (MIT) and was one of the most investigated AM techniques in tissue engineering and drug delivery applications. It is still quite promising of constructing scaffolds. One of the advantages of 3DP is that it can be performed in an ambient environment. A print head prints or deposits the binder solution onto the powder bed and after the cross-section (2D layer) profile is printed, a fresh layer of powder is laid down much like in SLS. The printing cycle continues and the layers merge together layer after layer when fresh binder is deposited until the entire part is completed. After that the binder needs some time to dry in the powder bed after which the finished component is retrieved and unbound powder is removed. (Hutmacher, Sittinger & Risbud 2004)

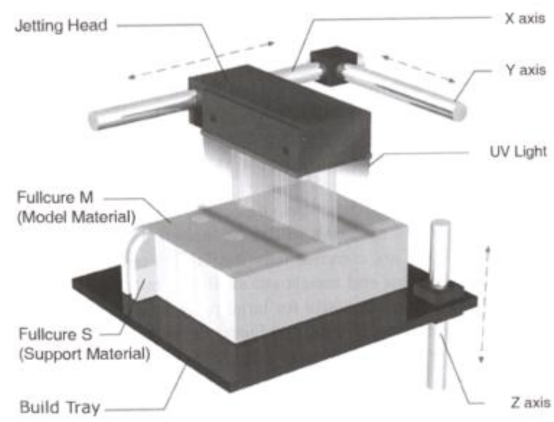

Figure 8: Objet Polyjet 3D printer build process (Gibson, Rosen & Stucker 2010)

Fused Deposition Modeling (FDM)

Fused Deposition Modeling is an AM technique which fabricates 3D parts by deposition of molten material layer by layer. In the process a spool of thermoplastic filament feeds into a heated FDM extrusion head and the movements of the head are controlled by computer. The filament is heated to liquid inside the extrusion head before it is applied to the model. The extrusion head traces an exact outline (x and y directions) of each cross-section layer by layer. After a layer is

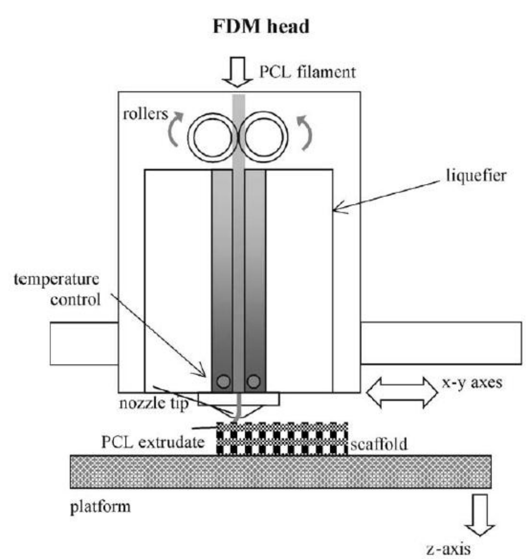

Figure 9: A schematic diagram of FDM extrusion and deposition process (Zein et al. 2001)

finished, the extrusion head moves up (z-direction) a programmed distance and begins the production of a new layer. Each layer is bonded to the previous one through thermal heating. (Saleh & Dalgarno 2010) (Yan & Gu 1996)

The FDM technology allows a variety of materials and colors for model building. These materials include wax-filled plastic adhesive material, proprietary nylon and a commonly used material is acrylonitrile butadiene styrene (ABS). ABS is rigid, has dimensional stability, has thermoplastic properties and is quite inexpensive. (Yan & Gu 1996) (Winder & Bibb 2005)

In medical context the advantage of this method is that it could be placed in a hospital environment because of its small size. There is a machine called Medmodeller (FDA certified), which is based on FDM technology and it is meant to be used in hospital environment. (Marciniec & Miechowicz 2004)

2.5 Dynamic Web Applications

The empirical part of this research focuses on building a website, or rather a web service, to broaden and bring together information and knowledge about medical applications of additive manufacturing. The main objective is to construct a process model to depict how the process of manufacturing medical models using AM actually works and bring it out for professionals interested in the field. A good way to bring it out to the public is to come up with a database solution and a web interface. There are a number of technologies that could be used to produce the same solution but for the purpose of this research Linux Ubuntu, Apache HTTP server, MySQL relational database management system (RDBMS), PHP general-purpose scripting language and Drupal 6 content management system (CMS) were selected.

The reasoning behind selecting these techniques is explained in the following chapters.

2.5.1 A Word for Open Source Initiatives

The term open source was coined in 1998 when Netscape published its browser’s source code. This idea of free and open software was not a new one in programming communities but after this announcement open source ideology became more known and it started to gain more popularity. (Naramore et al. 2005)

Linux became the first operating system that could be considered open source and after that many programs followed. The Medical Applications of Additive Manufacturing website runs on Linux Ubuntu 10.04 operating system, uses MySQL relational database management system and Apache web server and is built on Drupal 6 content management system. All of these programs are freeware, a part of the open source movement and operate under some free software license, most commonly GNU General Public License (GNU GPL). GNU GPL is the most widely used free software license and it is originally written by Richard Stallman for the GNU Project. This thesis project, with many other alike, owe a great deal to the open source movement for making it possible to produce database driven applications to share information and create services in a cost efficient way.

2.5.2 Linux Ubuntu 10.04

There was a need to build a server that runs the website. Linux Ubuntu (server edition) 10.04 was selected as an operating system and installed to an older PC. Server edition does not include a graphical operating system but a light Xfce desktop environment was installed for easing the configurations. Xfce desktop environment is much lighter than GNOME (GNU Network Object Model Environment) or KDE (an integrated set of cross-platform applications) and a good choice for use on older or less-powerful systems which was the case. (von Hagen 2010)

One big part of the project was to configure Linux to be an efficient server environment for the project's needs and all the other server needs of IDM group. A lot of configuration was needed in order to create an efficient and secure server. Without going into details here are a few tasks that needed to be done to configure Linux for the project's needs:

- Installing a selection of applications, LAMP (Linux, Apache, MySQL, PHP) server software being the most important ones
- Configuring users and privileges
- Configuring Apache server
- Creating SSH tunnel and restrictions for the connections

Linux offers a good platform to build a server and the most reliable and the simplest solution for this project was to use LAMP server. LAMP is an acronym for a stack of open source software, more specifically Linux, Apache HTTP Server, MySQL and Perl/PHP/Python which are the components that one needs to build a viable general purpose web server. (Lee & Brent 2002)

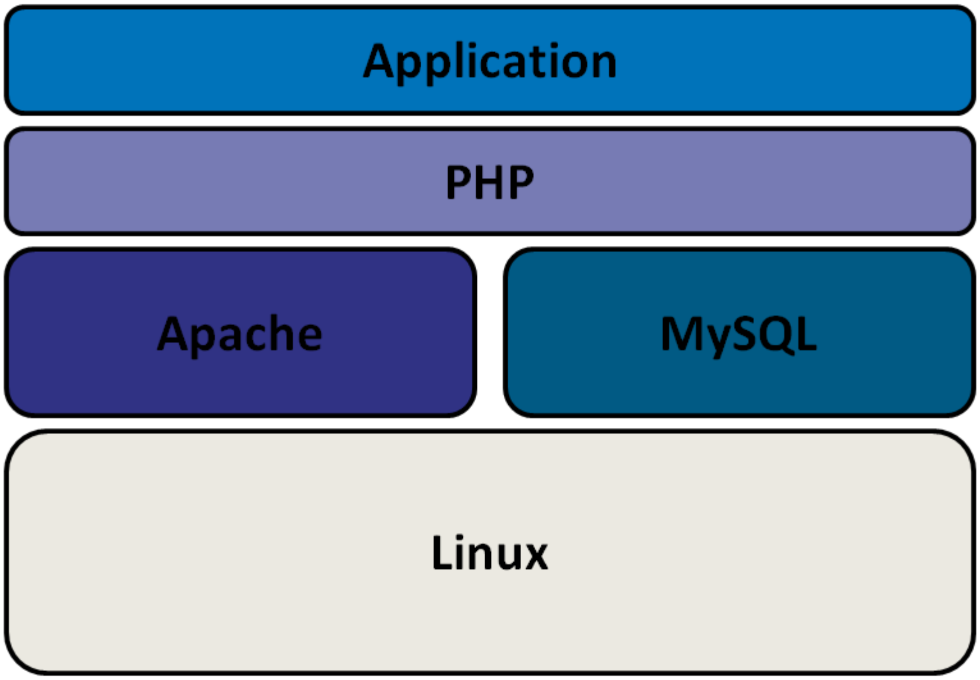

Figure 10: LAMP Stack

Figure 10 above depicts the LAMP stack which is needed for building a viable web server. Each of these components will be examined briefly in the following chapters.

2.5.3 Apache HTTP Server

Apache is a dominant web server on the internet having a very crucial role in the infrastructure of the Internet today. What a web server does is that it translates a URL either into a filename and then sends that file over the internet, or into a program name, which is run and the output is sent back. (Laurie & Laurie 2003)

Major reasons for choosing Apache: (Laurie & Laurie 2003)

- It is freeware and under GNU General Public License
- Runs fast, can cope with a lot of requests using a minimum of hardware
- Supports multitasking
- Supports a variety of formats
- Can run as a proxy server

- Is secure

As Figure 10 shows, Apache server works side by side with MySQL RDBMS on Linux operating system.

2.5.4 MySQL RDBMS

As discussed previously, the goal of the project was to build a website for medical application of additive manufacturing. Quite early in the project it became clear that a static, unchanging, website would not meet the requirements and a database based website was needed. This is when MySQL is comes to play. Databases and database management systems have really become the backbone for many applications, including web-related, that rely on data stores to support dynamic information needs. Databases are flexible, scalable data sources that are involved in almost everyone's life whether they know it or not. Renting movies, selling books, booking tickets are all services that depend heavily on database systems. (Sheldon & Moes 2005)

SQL is a computer language used to manage and interact with data in a relational database. It has become the standard language for database management and it is the most universally implemented database language. SQL works in conjunction with a Relational Database Management System (RDBMS) to define the structure of the database, store data, manipulate data, control access, retrieve data, and to ensure the integrity of the data. (Sheldon & Moes 2005)

MySQL is a RDBMS that covers database needs from home servers to demanding company networks.

Reasons for selecting MySQL:

- MySQL is open source
- It is fast, reliable and easy to use
- It works in client/server and in embedded systems
- There are a large amount of contributed MySQL software available

2.5.5 PHP: Hypertext Preprocessor

PHP is a web development language, more specifically server-side scripting language, which can be embedded in HTML. For example, you can use PHP to store form submitted data to database, add common headers and footers to all pages and much more. (Converse et al. 2004)

The basic idea behind a database driven website is to allow the content of the site to reside in a database, and for that content to be pulled from the database dynamically to create web pages. As people use their browsers to view web pages, browser sends a request to the database via PHP script and expects to receive a standard HTML document in return. At the other end you have the content of your site, which is in MySQL database that understands only how to respond to SQL queries. (Yank 2009)

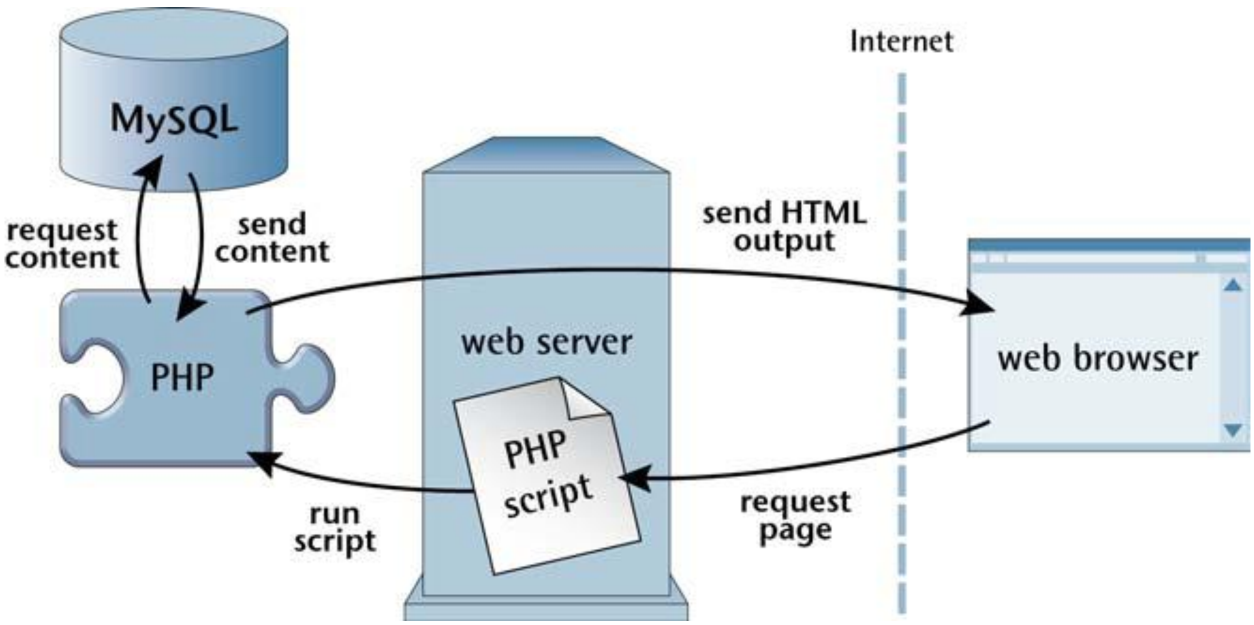

Figure 11: How PHP, MySQL and Apache work together (Yank 2009)

Figure 11 shows how dynamic web pages are created with web server (Apache), PHP and MySQL. The PHP scripting language is the go-between that speaks both languages needed, HTML and SQL. This is a step-by-step illustration what happens when someone visits your site. (Yank 2009)

1. The web browser requests the page using a standard URL.
2. Web server (Apache) recognizes that the request file is a PHP script, after which the server fires up the PHP interpreter to execute the code.
3. PHP commands connect to the MySQL database and request for data.
4. The MySQL database responds by sending the requested data to the PHP script.
5. The data is stored into one or more PHP variables by the PHP script, and echo statement is used to output the content in the variables.
6. The PHP interpreter finishes up by handling a copy of the HTML it has created to the web server (Apache).

7. Finally the web server sends the HTML to the web browser as it would a plain HTML file, except that instead of coming directly from and HTML file, PHP interpreter provides the output.

2.5.6 Application

The final block in the LAMP stack (Figure 10) is application. In this project the application block means the final Medical Applications of Additive Manufacturing website but it also contains one building block that is essential in the creation of the site. That building block is Drupal.

Content Management System Selection Process

There was of course an option to build the site from scratch using PHP programming but it became clear quite early in the project, after consulting WWW-technology savvy people at the Aalto University, that it would be more efficient to use a Content Management System (CMS). After deciding that CMS was the way to go there was still the debate about which CMS to use. There are literally hundreds of CMSs available and all of them have characteristics that make them better or worse depending on the functionalities needed. I decided to find out which would be the most important functionalities that CMS needed to offer in order to create the Medical Applications of Additive Manufacturing MAAM site.

Based on the expectations for the site and the time constraint that I had for the project, I gathered the most important functionalities that a CMS should offer:

- Ease of use – how effortless is to build basic functionalities
- Core functionalities – creating, deleting, editing and organizing pages
- Managing assets – image and file management
- Search – most efficient search functionalities
- Customization – technology should not limit customization possibilities
- Theme customization – front-end theme development
- Roles and permissions – control over who can edit what content
- Multiple website support – ability to build subsites

Three of the major open source CMSs were examined following the criteria above. Wordpress, Joomla! and Drupal are among the most used open source CMS at the moment.

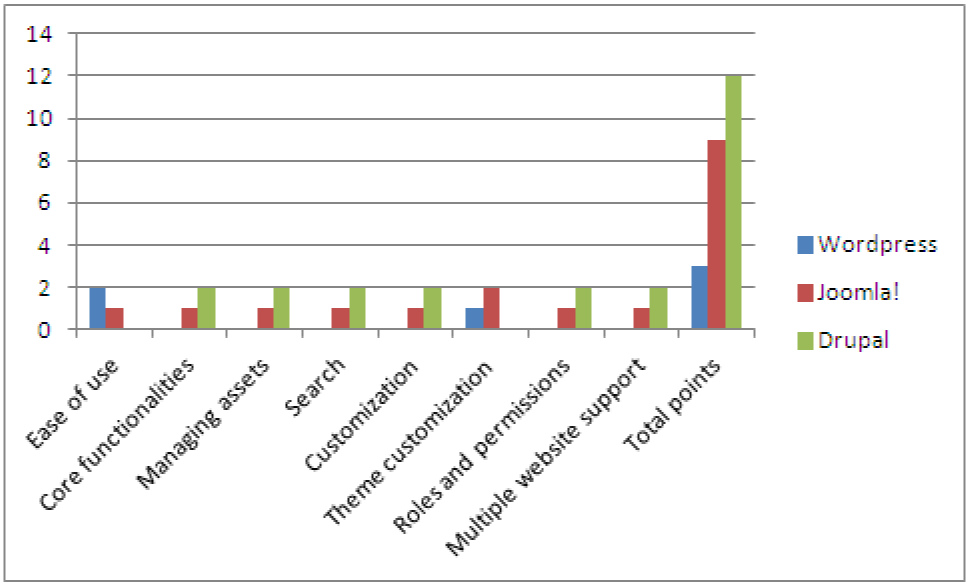

Figure 12: Comparison of Wordpress, Joomla! and Drupal

Figure 12 shows the comparison of the three CMS in question. Each CMS is compared against each other in each category. Points are given by position. The winner of the category gets two points, second gets one point and loser gets zero points. According to total points Drupal is the best, Joomla! is second best and Wordpress is the worst to qualify as a CMS for MAAM site. Not only Drupal wins in points but it wins in managing assets, customization, and roles and permissions categories that I weigh to be most important ones for this implementation. From these results Drupal was an easy choice.

The comparison is made by examining online articles and discussions with more experienced users. These results are subjective but they should reflect the general opinion of the CMSs in question regarding these categories.

What is Drupal?

Drupal is a content management system (CMS) that enables the user to build large scale dynamic websites by using prewritten modules and functions which makes it possible to produce website projects quicker than it is usually possible by doing everything from the scratch using PHP and HTML programming. CMS is a software package that provides the needed tools for authoring, publishing and managing content on a website. This content can be anything from blog post, videos, and news articles to product information. CMS usually provides a set of features that simplify the process of building, deploying and managing a website (Tomlinson 2010):

- an administrative interface
- a database repository for content
- a mechanism for associating information that is stored in the database with a physical page on the website
- a toolset for authoring, publishing, and managing content
- a component for creating and managing menus and navigational elements
- the tools required to define and apply themes
- user management
- a security framework
- Web 2.0 capabilities such as forums, blogs, wikis, polls, and surveys
- taxonomy and tagging
- online forms
- e-commerce capabilities

Drupal is free and open source CMS and it is distributed under GNU General Public license. This means that it is free for anyone to use for their private, or business purposes. The open source community is also very active to constantly develop its products making them more robust and usable. Using a CMS brings more possibilities during the thesis work to add and test out different functionalities on the website. If I had to code everything by hand I would be limited to very a few functionalities that the website can have because of the limited time that is allocated to the project. Drupal makes it possible to design a broader and more user friendly site with collaborative functions in just a few months.

Drupal is also a good choice regarding future development. The purpose of this project is not to produce a static website that has limited development possibilities but a base website with core functionalities that can be developed to a bigger site in the future if needed. For this Drupal gives you all the freedom you need and helps you on the way. Modules, which are the basic building blocks of Drupal, are constantly developed by the Drupal community. This way new functionalities can be added to the website with little coding effort from developer's part. And on the other hand, Drupal is almost as flexible as a CMS can be. It allows you to code your own modules and tweak the system with PHP snippets that you can write yourself.

3 Empirical Study

3.1 Materials and Methods

A lot of MAAM related material in this thesis is from IDM group's database that the group has assembled in several of its previous projects. This thesis project is based on four different projects by IDM group which are presented in this chapter. A lot of information and knowledge gained from those projects have been used especially in the medical and additive manufacturing sections of this thesis. Also the case information presented on the MAAM website is based on work done during these projects. In the next chapter there is a brief introduction to these projects.

3.1.1 Projects

Bioman[1]

Bioman project focused on reviewing the state of medical grade materials in additive manufacturing in 2005-2006. It was financed by TEKES (the Finnish Funding Agency for Technology and Innovation) and participating companies. The main focus was to find out how biomaterials, developed especially by Tsinghua University but also generally worldwide, can be utilized in tissue regeneration. (Paloheimo & Tuomi 2006)

Results from the project included a comprehensive list of institutes around the world which are doing research in this field, an interdisciplinary vocabulary, a database of publications and a preliminary classification of medical applications of additive manufacturing. (Paloheimo & Tuomi 2006)

Bioman II[2]

After Bioman project there was a clear need for continuation of the same theme. The goal of Bioman II was to advance the development of viable service business opportunities around rapid manufacturing of biomaterials and medical applications of additive manufacturing. The research

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[1] Bioman II, Tekes (283/31/07), 2010-2012

[2] Bioman, Tekes (103/31/05), 2005-2006.

was focused on understanding the process of manufacturing medical applications of additive manufacturing, and as a result, the project produced a publication and a classification matrix that has been one of the cornerstones of this thesis research. (Tuomi 2010) (Tuomi et al. 2007)

It has been noticed that the process of manufacturing medical applications by additive manufacturing is quite difficult and complex task that needs multidisciplinary knowledge. There has not been a research group in Finland that has been able to do that until Bioman research group was established. During the project it has been identified that understanding of the entire process chain is crucial to enable real, commercially viable, design and production of medical applications of additive manufacturing. (Tuomi 2010) (Tuomi et al. 2007)

3D MedAman[3]

A classification system for medical applications of additive manufacturing was developed in Bioman II project. 3D MedAman continues from there focusing on areas in classification 1-4 (Preoperative models, inert implants, medical aids & prostheses, and tools & instruments) and classification 5 (biomanufacturing) is a separate project called FidiPro BioScaf. Timelines for the project can be seen in Figure 13.

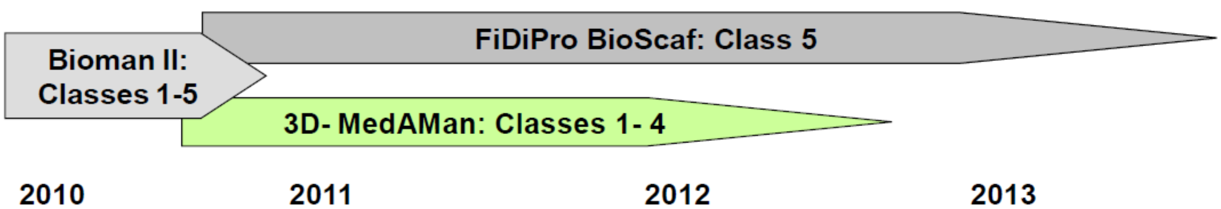

Figure 13: Timelines of Bioman II, 3D – MedAMan and Bioscaff projects (Tuomi et al. 2010)

The next five goals were identified with two main criteria: 1) Development potential of commercial products and services on clinical applications and 2) scientifically challenging but realizable doctoral-level research. (Tuomi et al. 2010)

I. Implementation of the matrix in the development of clinical applications, co-operation with different actors in a way that uses the concept in the realizations of products and services in this field.

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[3] 3D MedAman, Tekes (660/31/2010), 2010-2012.

II. Creation of new knowledge related to medical imaging and digitizing methods and the combination of the two; the development of quality processes in medical 3D – modeling.
III. Development of better interactive group related tools for handling medical 3D – models.
IV. The development of material- and quality technology for the clinical use of inert implants while ensuring the safety of patients; producing documentation in accordance with EU directives and other clinical research regulations.
V. The integration of medical imaging, digitizing, and modeling of anatomical movement especially in the field of post-operative applications of additive manufacturing.

This thesis project is heavily involved in realization of goals I-II. A web based application of the matrix is needed to educate the community about our way of classifying and thinking about the process (I). Imaging quality is an important factor in the success of additive manufactured pieces. For that, it is an important area of study when defining relevant parameters/attributes for the first process step in the matrix (II).

FidiPro Bioscaff[4]

FidiPro Bioscaff is a close collaboration project with Tshinghua University (China). The general aim of the study is to bring and create new expertise in biomanufacturing research and development in Finland by exploiting the expertise of professor Wang and her colleagues from Tshinghua University. (IDM website 2011)

The expected results of the project are (IDM website 2011):

a) to find optimal cell culture conditions for the selected scaffold materials

b) to monitor cell division, differentiation and migration of selected cell types

c) to monitor cell-to-cell and cell-matrix interactions of selected cell types

d) to monitor biodegradation rate of various scaffold materials in a 3D environment using 3D biomaterial scaffold specimens in cell culture.

The thesis project aims to incorporate elements from this study to the web application or, at least, make it technologically feasible to modify the matrix to fit the special needs of biomanufacturing in the future.

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[4] FidiPro Bioscaff, Tekes (2926/31/2009), 2010-2013.

3.1.2 Empirical Research Methods

Literary review was an important part of the research to understand the theoretical background of all the topics covered in the thesis. However, theoretical background does not suffice in the empirical development phase. Methods for acquiring more detailed professional knowledge about additive manufacturing, medicine and web development required more interactive approach.

In the matrix development, many team meetings were held where the research group director and one or two additive manufacturing specialists were present. Based on literary review I presented my matrix development suggestions which were then discussed in the group. Based on discussions I modified the matrix and after an iterative process of many meetings the final form of the matrix started to shape. My aim was to engage discussion based on my theoretical research and then take more facilitative role and document the results of the discussions.

The first process step, which included medical imaging, was a difficult topic from the start because IDM research group does not have strong knowhow in radiology. This problem was overcome by interviewing radiologist from Helsinki University Central Hospital (HUCH).

IDM group has ongoing MAAM cases and I was able to participate in team meetings where engineers and doctors tried to find solutions for patient cases. Even though this experience did not directly help me with the development work, it made me understand some of the common problems in interdisciplinary team work. These problems were usually lack of common vocabulary and visualization tools which complicated team work. These aspects are taken into consideration in the future development recommendations for the web application.

For web server and web application development I did not have any direct support from IDM group. For web server development I turned to IT personnel of BIT Research center and did interviews and had many discussions about best practices. On web application development I mostly relied on Drupal community support forums as I found out that this was sufficient enough to tackle the obstacles for which I needed help in the development phase.

3.1.3 Case Approach & General Cure Approach

The MAAM case data used in this research can be divided into individual cases and general cure development. Individual cases are, for example, operations where a patient specific solution is produced and the operation is not easily repeatable. Orbital implant case is one example of individual cases where patient’s orbital wall was reconstructed.

On the other hand, there are projects that aim to develop more general tools that can be thought as general cures for specific injuries. This means that the device produced can be used for several similar cases with minor modifications. One example is external ankle support project (Figure 17) that IDM group has done. In the project a device was designed and produced to enhance rehabilitation of ankle injuries. This project has produced a tool that can be used in many ankle injury cases, requiring only small modifications on the device.

3.2 Medical Applications of Additive Manufacturing: Matrix Development

Focus of this chapter is to apply research done in previous chapters to MAAM context. The classifications, as well as the process steps, are depicted more thoroughly. The starting point for this research is shown in Figure 2 and more developed matrix is show in Figure 14.

	Medical Imaging & 3D Digitizing	3D Modeling	Additive Manufacturing	Finishing	Clinical Application
1. Preoperative models					
2. Medical aids, supportive guides, splints and prostheses					
3. Tools, instruments & parts for medical devices					
4. Inert implants					
5. Bio-manufacturing					

Figure 14: General Matrix for Medical Applications of Additive Manufacturing

The order of the classifications in Figure 14 has changed compared to the original matrix (Figure 2). The original matrix had no logical reasoning behind the order of different classifications. The order in this matrix reflects the closeness of the additive manufactured piece to the patient as follows. 1. Preoperative models include anatomically specific models that can be used in preoperative planning and communicating and they have no physical contact to the patient. 2. Medical aids, supportive guides, splints and prostheses have external body contact and are not invasive. 3. Tools, Instruments & Parts for Medical Devices contain devices that may have contact with body fluids, mucous membranes, tissues and organs for a limited time. Devices in this class are invasive but not implantable. 4. Inert implants are wholly or partly implanted and they have long term contact to body fluids, tissues and organs. 5. Biomanufacturing means biologically active tissue replacement which means that they are incorporated into body. To sum, the higher the number of the classification the closer to patient's body will additive manufactured piece be used. (Paloheimo et al. 2011)

The process steps (x-axis), which are explained in detail in chapter 3.2.2, have been quite generally known for years. As you can see in Figure 15, the process of making preoperative models is depicted quite the same way as in the MAAM matrix.

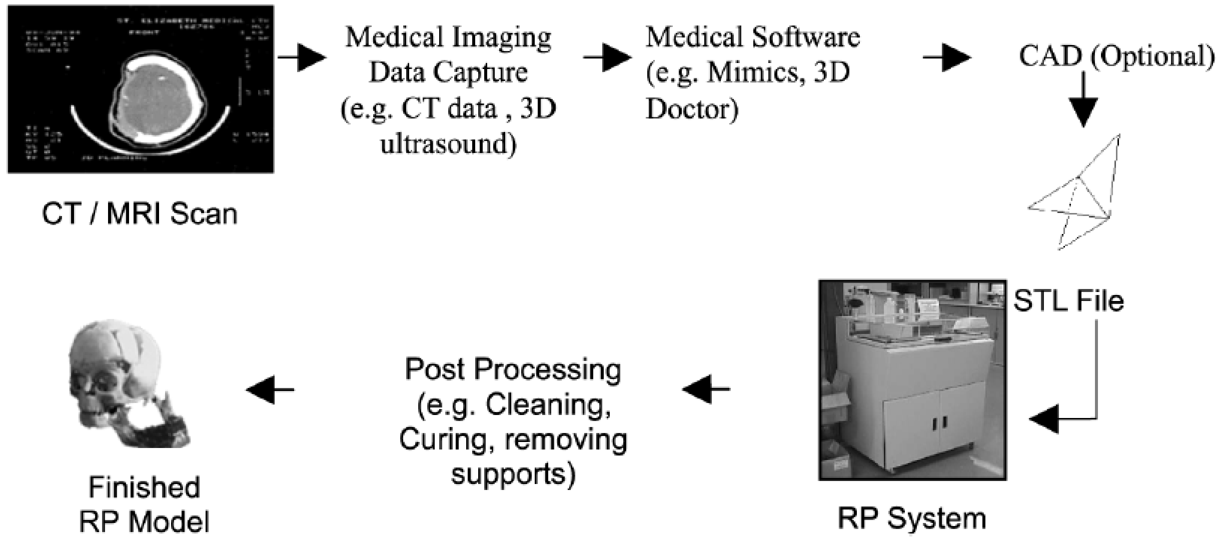


Figure 15: Generalized procedure for creating medical models (Gibson et al. 2006)

The added value that this research brings to the process is that it breaks down every step to smaller sub-categories trying to find all the relevant technologies and parameters/attributes in each step. This will help to examine medical application cases and compare them when all the relevant information of the manufacturing process is given.

3.2.1 Classifications

1. Preoperative Models

Preoperative models were the first medical applications of additive manufacturing. Already since the 1980s preoperative models have been used for maxillofacial, orthopedic and oral applications when they were manufactured using five-axis CNC machines which had limitations in terms of undercuts and thin cross sections. Introduction or rapid modeling, or additive manufacturing as it is called now, eliminated these short comings. (Brennan 2010)

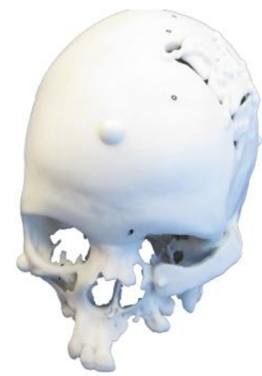


Figure 16: Preoperative skull model

Preoperative models are anatomically correct representations of a region in human body. Models are most commonly used in complex surgery to ease the planning process. These models can be useful both to doctors and patients in many ways. The main purposes of preoperative models are to plan or simulate a procedure, give better visualization of anatomical features, for training and education and to enhance doctor-doctor as well as doctor-patient communication. (Marciniec & Miechowicz 2004)

An actual, haptic model facilitates the diagnosis of the problem and simplifies the study of the shape, location and size of an anatomic structure. Parts of the model can also be colored for better understanding of the defect area. These models can be used in many stages of complex surgery. Models make it possible to examine defected area from any angle which reduces ambiguity, makes communicating the problem and the solution easier and it also can be a design template for prosthetics and implants. (Marciniec & Miechowicz 2004)

There are also studies that show that using preoperative models can reduce operation times which reduce risk of infection during and after surgery. This also makes the procedure cheaper. Medical models can also play an important role in improvement of undergraduate and postgraduate training skills in medical education. Models are very close to the human form and have qualities of the human form and, therefore, are ideal for the practice of surgery. (Hieu et al 2005)

2. Medical Aids, Supportive Guides, Splints & Prostheses

Improvements in CT have enabled more precise imaging and thus more specific models. As the cost of imaging and AM has come down it is possible to produce patient-specific devices that enhance healing from trauma, anomaly or defect. This classification includes external prostheses and prosthetic sockets, personalized splints, drill-guiding microtables, orthopedic appliances and braces to name a few. Devices in this class may also be combined to standard devices to provide patient specific fit. Basic requirements are non-allergic materials if in contact with skin and mechanical and surface structure requirements depend on the case needs. (Paloheimo et al. 2010)

Prosthetic sockets are one example in this class. Creating a socket has traditionally been a labor intensive task but with the help of computer aided manufacturing (CAM) systems and AM technologies the manufacturing time can be decreased from three days to less than 4 hours. (Tuomi et al. 2010)

Figure 17 shows an external ankle support for ankle injuries. With this device patients can begin their ankle's rehabilitation early. Additive manufactured pieces make sure that the line of movement in patient's ankle is correct which will enhance and ease the process of healing.

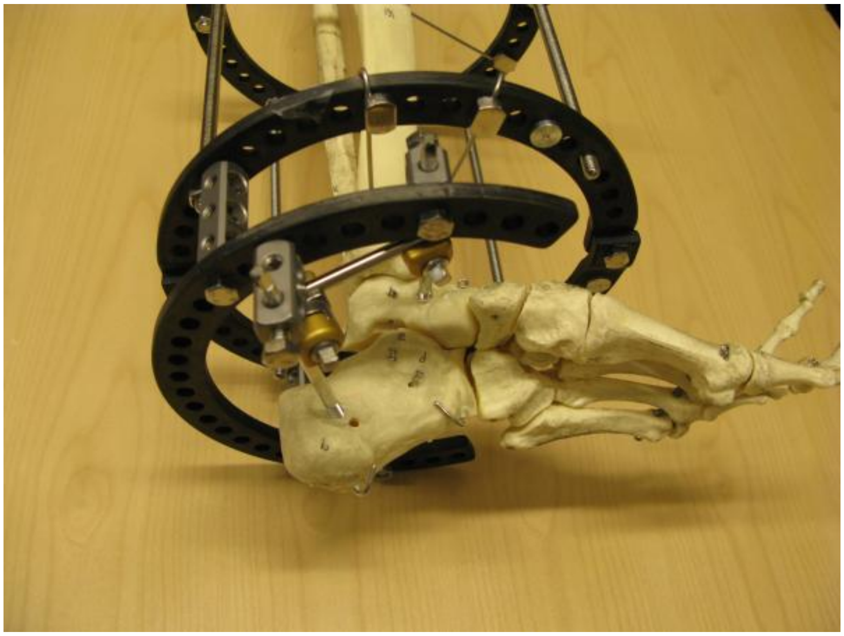


Figure 17: External ankle support

3. Tools, Instruments & Parts for Medical Devices

Surgical aid tools are important tools to enhance surgeon's skills during the operation. For example, drill guides can increase accuracy and safety, reduce operation and overall costs, and enhance the outcome of surgery. (Hieu et al. 2005)

Tools might have contact with body fluids, mucous membranes and tissues so they are invasive but still not implantable. Patient specific dimensions and shapes may be incorporated. For devices in this class there are stricter requirements than in the two previous classes. Tools that have in vivo contact need to be sterilized and may not shed any particles during operation. Devices have stricter material requirements due to toxicity risks. (Paloheimo et al. 2010)

Figure 18 shows a surgical aid which is used as a guide for removing a bone tumor in patient's skull in one-step cranioplasty operation. The tool and the implant are designed at the same time and the implant is placed after the tumor is removed. The benefit of this kind of procedure is that, instead of using two operations, surgeons need only one operation for the treatment. This reduces risks, is cheaper and a more practical for both the surgeon and the patient. (Hieu et al. 2005)

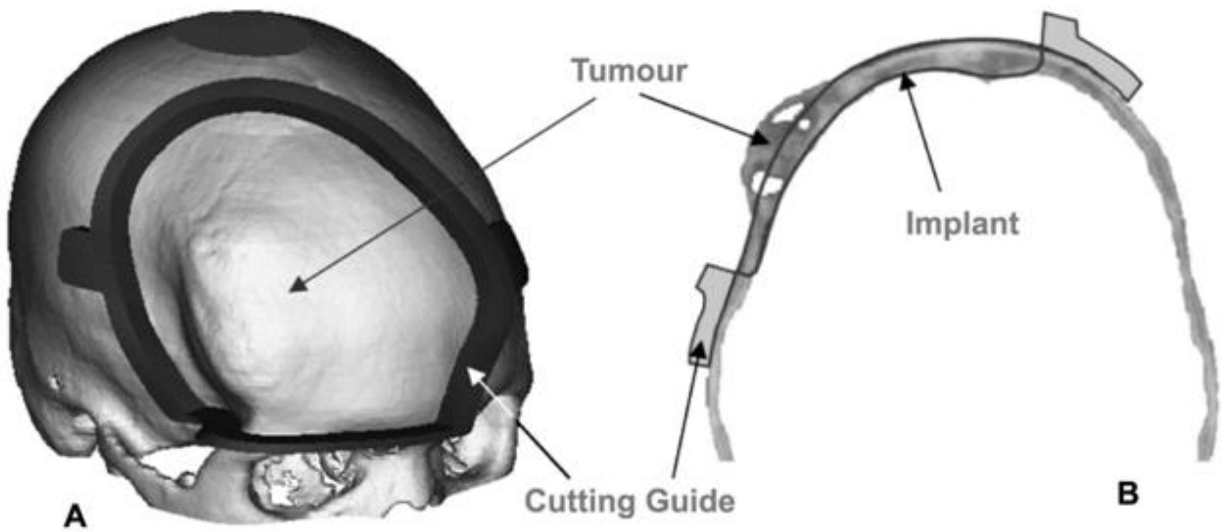


Figure 18: (A) A guide for removing the bone tumor (B) Final check on patients CT images (Hieu et al. 2005)

4. Inert Implants

Possibility to produce anatomically accurate implants before operation not only makes it possible to have extremely well fitting implants but it can also decrease operation time significantly. There are standard implants of different sizes which are used in most cases but there is a need for customized implants in areas where geometrical complexity increases. With medical imaging data and CAD/CAM software it is possible to design very accurate implants that are patient specific and these geometrically accurate implants are preferred by many surgeons. (Marciniec & Miechowicz 2004)

Inert implants have strict material requirement because they are implanted in the body permanently. Durability, mechanical properties and surface properties become a very important issue. The implant should in most cases stay inactive and not change its characteristics in vivo. Surface treatments, like sterilization and polishing, are very important aspects that need to be taken into consideration when selecting materials and manufacturing technologies for inert implants. (Paloheimo et al. 2010)

Figure 19 shows an orbital wall implant that was designed by IDM group to repair a difficult facial trauma. The implant is a titanium reconstruction plate that was additive manufactured and implanted onto injured orbital wall of patient.

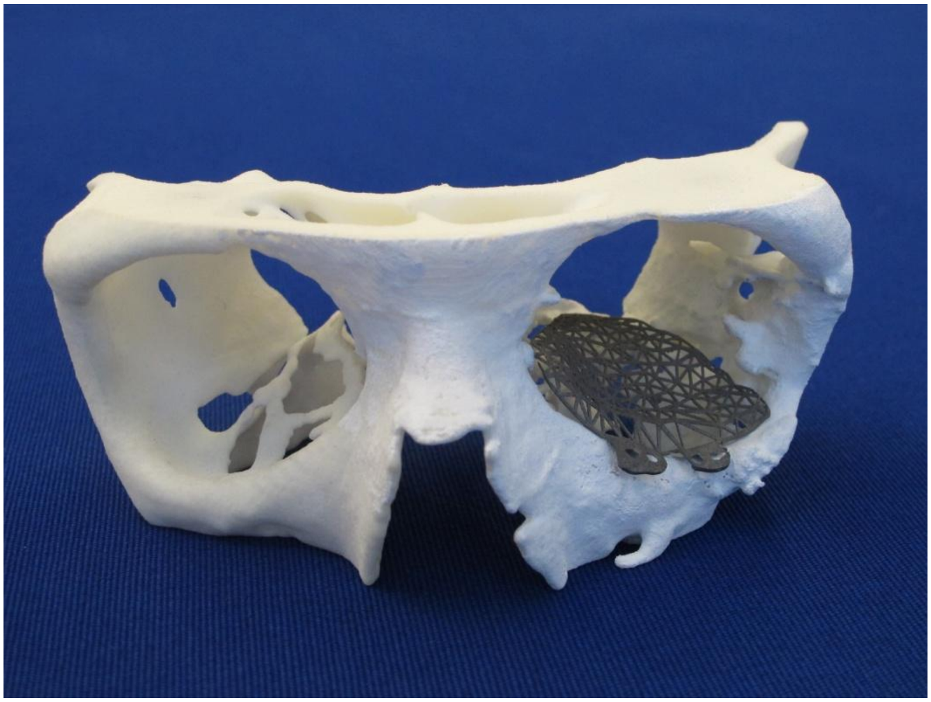


Figure 19: A preoperative model and the orbital implant

5. Biomanufacturing

Tissue engineering is an emerging field in which research efforts have been continuously growing in the past years. Tissue engineering may make it possible to regenerate or replace damaged tissue with laboratory-grown parts which can be bone, cartilage, blood vessels or skin. The main concept is to combine a scaffold, living cells and biologically active molecules for a 'tissue engineering construct' (TEC) to promote the repair and regeneration of tissues. Scaffolds for tissue engineering are designed through CT/MRI and micro-CT image processing and geometrical modeling techniques after which additive manufacturing is applied to fabricate the scaffolds. (Hutmacher 2005) (Hieu et al 2005)

The scaffold material is a very important aspect. It should be non-antigenic, non-carcinogenic, non-toxic and non-tartogenic as it will be implanted in the human body. High cell/tissue biocompatibility is important so that the scaffold will not trigger any adverse cellular reactions after implantation. Macro- and microstructural properties are also important because the scaffolds require individual external shape and well-defined internal structure with interconnected porosity. Additive manufacturing with its ability to produce any kind of internal and external structures is an optimal technology for this task. (Hutmacher 2005)

Scaffold's functions

The main purpose of scaffold is to mimic the structure and functions of extracellular matrix. The primary roles can be divided as follows: (Yeong et al. 2004)

1. Serving as an adhesion substrate to the cell, and facilitating the localization and delivery of cells at the moment of implantation.
2. Defining and maintaining a 3D structure to provide temporary mechanical support to the newly grown tissue.
3. Facilitating and guiding the development of new tissue with the appropriate function.

Also, a successful scaffold should have suitable macrostructure to promote cell proliferation, an open-pore geometry with a highly porous surface and microstructure to enable cell in growth, an optimal pore size to encourage tissue generation, and the scaffold should be made of material with a predictable rate of degradation. (Yeong et al. 2004)

Figure 20 below depicts some of the possible uses of scaffolds in tissue engineering.

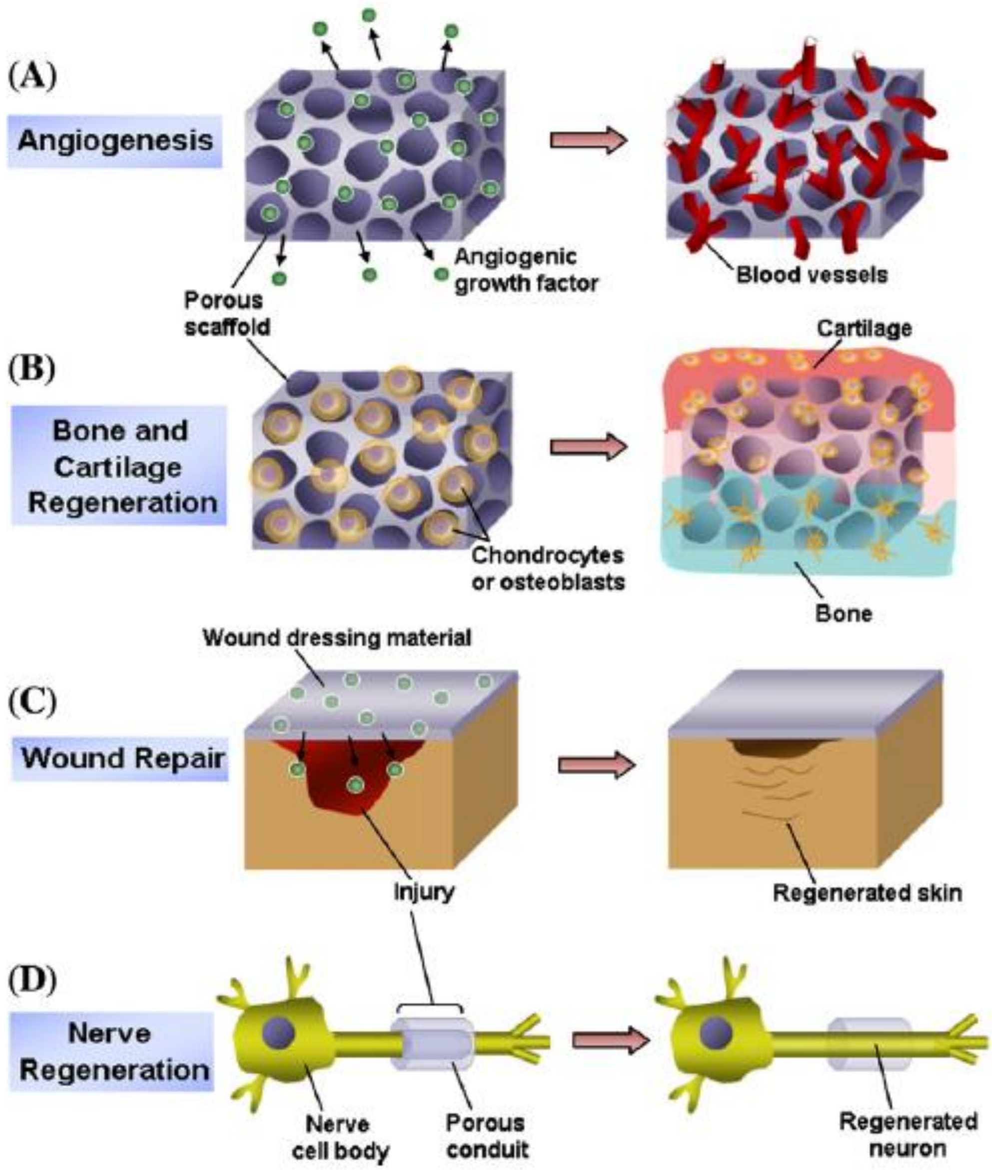


Figure 20: Multi-functional scaffolds for regenerating of various tissues: (A) Scaffolds delivering angiogenic growth factor to induce blood vessels (B) Scaffolds filled with osteoblasts/chondrocytes for bone and cartilage regeneration (C) Film that releases growth factors for wound (D) Porous conduits for nerve generation. (Chung & Park 2007)

3.2.2 Matrix Process Steps

This chapter explains how the process steps (x-axis in Figure 14) in the MAAM matrix has been developed and which subcategories are chosen to be relevant for each step in the process flow. The findings in this chapter are based not only on literary reviews but also team meetings with the IDM group where these steps have been discussed and key phases of each step are have been decided.

Medical Imaging & 3D Digitizing

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

Figure 21: Medical Imaging & 3D Digitizing process step

In order to manufacture an additive manufactured model of human anatomy it must first be digitized in a manner that allows computers to process the information. This information can be used in additive manufacturing process. A number of scanning technologies can be used, ranging from imaging machines in the radiology department, to small hand-held scanners used in laboratories and clinics. (Bibb 2006)

In MAAM matrix, the process flow begins with the capture of geometrical information of a three-dimensional object. There are different methods for acquiring the data in MAAM context. Here are examples of technologies in this group. We can group **Medical imaging & 3D digitizing technologies** (first subcategory of Medical Imaging & 3D Digitizing) in 3 categories: (modified from Galantucci 2010)

Based on transmission:

- X-ray computed tomography (CT)
- Cone beam computed tomography (CBCT)
- Magnetic resonance imaging (MRI)

Medical imaging, and CT especially, is the most common way to acquire anatomical three dimensional information at the moment in MAAM context. It is accurate and many cases involve bone related defects for which CT is the ideal imaging modality. CBCT is also used for bone defects and MRI is for soft tissue imaging but these techniques are not used as often as CT.

Based on contact:

- Coordinate Measuring Machine (CMM)

CMM can be used for surface measurements or, for example, measuring trajectories of hand or leg movement.

Based on reflection:

- Ultrasound (cyclic sound pressure)
- Stereovision (triangulation)
- Laser (triangulation)
- Moiré (interferometry)
- Conoscopic Olography (interferometry)
- Grey Codes (structured light)
- Linear Arrays (structured light)
- Patterns (structured light)
- Shapes from profiles (image analysis)
- Shapes from silhouette (image analysis)
- Depth from focus (image analysis)

CMM can be used to capture the external shape or skin surface but it is frequently more practical and comfortable for the patient to use non-contact scanning systems. These systems typically rely on light-based techniques to calculate the exact position in space, from points on the surface of an object. After this a computer program is used to create surfaces of an object. (Bibb 2006)

This category has many different technologies which all rely on reflection. Ultrasound can be used to examine internal organs. All the other technologies in this category measure external 3D shapes using triangulation, interferometry, structured light, or image analysis. Many of these technologies are not considered regular medical imaging modalities and are not very popular at the moment but are still used in some dental applications and plastic surgeries. Figure 22 shows an example of laser scanning used in the process of creating an ear prosthesis. Laser scanner scans the healthy ear and exact replica is made from the 3D data. This replica is placed on the defective side of the patient.

Figure 22: A) Laser scanning of the healthy ear B) Laser scanning of the defective side C) Testing with the mirrored ear (Ciocca et al. 2009)

Second subcategory, **commercial machines,** is for documenting the commercial machine used in the process, e.g. Philips CT 64-Channel Scanner. Documenting this information is important because imaging machines may vary quite a lot depending on manufacturer. Same parameters used in same kind of devices but from different manufacturers might not give exactly the same results. In practice, this way we can determine the best parameters for each machine type, taking into consideration the manufacturer.

Third subcategory, **attributes/parameters**, documents all the necessary input attributes/parameters of the used device. For example, for CT scanners documented attributes are slice thickness, voltage, tube current, overlap, field of view, and matrix size. There are a lot more attributes that can be adjusted in imaging process, but according to discussions in IDM group and an interview with radiologist from Helsinki University Central Hospital (HUCH), these are the ones that should be documented in order to be able to reproduce the desired imaging quality.

3D Modeling

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

Figure 23: 3D Modeling process step

3D modeling is a process of creating 3D surface models (STL mesh format) from 2D imaging slices (DICOM raster format). During the reconstruction phase all useless elements are being removed from the model. These elements can be distortions in the model, tissues not associated with the object of study, and other regions that are not of interest. These stages can be performed in reconstruction software such as 3D slicer or Osirix.

First subcategory is **reconstruction software**. There are a number of commercial and open source software available which all have their special characteristics. Some are better at some tasks than others so it is beneficial to document which software was used in each MAAM case.

Medical imaging devices (CT, MRI, etc.) produce pixel-based images in a series of slices. In most cases nowadays, this data will be available in DICOM (Digital Imaging and Communications in Medicine) format, which is a format that can be imported by most of reconstruction software. During importing, DICOM is converted to a format it recognizes as its own and displays the resulting axial images, which are the original scan images from CT data, on the screen. (Bibb 2006)

Usual reconstruction steps are thresholding and region growing. Thresholding is the term for selecting anatomical structures by specifying upper and lower density thresholds so tissues of certain density range can be isolated from surrounding tissue. Region growing refers to selecting single anatomical structures within specified thresholds. After these operations are done, three-dimensional images of the selected data can be produced. (Bibb 2006)

Second subcategory is **HU (Hounsfield) value**. Hounsfield scale is a quatitive scale describing radiodensity. The use of this standardized scale helps the intercomparison of CT values from different CT scanners and with different X-ray beam energy spectra. The system of units represents "an affine transformation from the original linear attenuation coefficient measurements into one where water is assigned a value of zero and air is assigned a value of -1000". (GE Medcyclopedia 2011) For example, the HU value of bone is generally +400 or more. Knowing these values helps to determine which threshold values to use in reconstruction phase.

Third subcategory is **CAD/CAM software**. After reconstruction is done the file can be imported to CAD/CAM software (in STL format) where additional adjustments can be made to the 3D image. Engineer can put markers or otherwise modify the 3D image or even design a patient specific implant on the spot, based on anatomical properties of the model. After desired operations have been done to the 3D image, it will be ready to be additive manufactured. Many different CAD/CAM software can be used to reach the same editing goals but these programs differ. Like in reconstruction phase, some programs are better at specific tasks. In order to find which one excels in which tasks, this information needs to be linked to each MAAM case.

Additive Manufacturing

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

Third step in the process flow includes elements and actors that are involved in the production of a physical piece. **AM technology** and **AM commercial machine** describe the technologies used in the production of the piece. **AM suppliers** tell us which company has been involved in the manufacturing phase. There is a wide variety of materials which can be used in AM processes, **AM material type** is for documenting that. These materials have different qualities and some materials are better for specific machines or purposes. **AM commercial material** gives the detailed information of the material used. **Layer thickness** describes the accuracy of the piece which can have a great impact in medical applications.

Some examples of possible content in subcategories:

AM technology

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Direct Metal Laser Sintering (DMLS)
- Selective Mask Sintering (SMS)
- Electron Beam Melting (EBM)
- LaserCUSING
- Selective Laser Melting (SLM)
- Laser Melting
- Direct Metal Printing
- Ultrasonic Consolidation (UC)
- etc.

AM commercial machine

- MCP Realizer SLM

- Z310plus
- EOSINT M270
- etc.

AM Suppliers

- Alphaform
- 3D systems
- Allied PhotoPolymers
- Arcam
- Beijing Yinhua
- CONCEPT Laser GmbH
- CRP Technology
- DSM Somos
- Envisiontec
- EOS
- ect.

AM material types

- Photopolymer liquid resin
- polyamide white
- Composite
- Plastic
- Titanium alloy
- Epoxy resin

AM commercial material

- YC-9300
- PA 2200
- ZP150
- DMX
- EOS Titanium Ti64
- Renshape SL-5220
- 316 Stainless steel
- Accura 60

Finishing

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

After the piece is manufactured it usually needs finishing. Finishing can mean various things, such as removal of supporting structures or polishing the surface. In medical applications **surface treatments** and **method of sterilization** are a critical factor which make them worthwhile to document. Examples:

Surface treatment methods

- Polishing
- Cosmetic Paint
- Non-Cosmetic Paint
- Rubberized Paint
- Vapor Polish
- etc.

Method of sterilization:

- Autoclave
- Gamma irradiation
- Ethylene oxide
- Hydrogen peroxide plasma
- Low temperature steam
- etc.

Clinical Application

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

The last step in the flow is the clinical application. It describes the name and the purpose of the application. Basically it is the application that a medical specialist uses before, during or after an operation, which can be a preoperative model or a surgical guide for example. The reader should note that many MAAM cases have several process flows. For example, in the case of orbital wall implant (Figure 24) the matrix has 2 process flows.

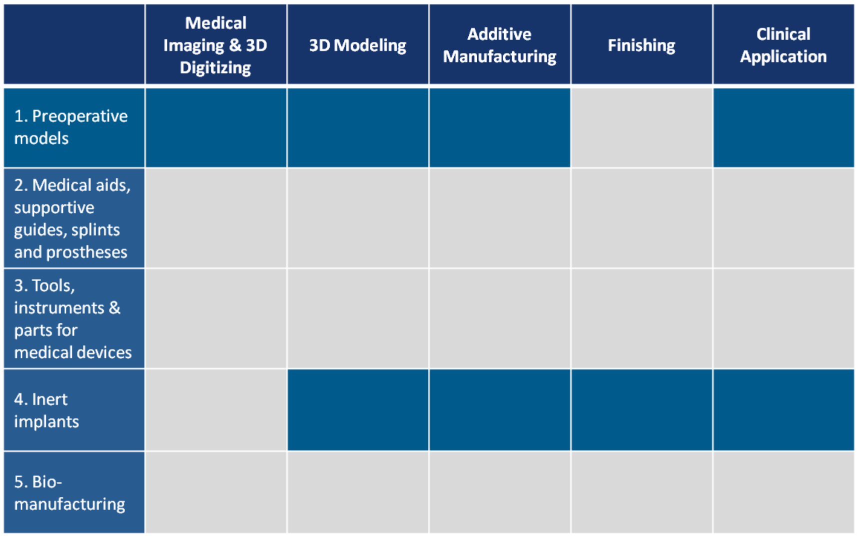


Figure 24: Process flows of orbital implant case

The first describes the production of a preoperative model used for planning the surgery and the second flow shows the steps involved in the design and manufacture of the actual implant. This case has two process flows and thus it has two different clinical applications, a preoperative model and an orbital implant. This is the real purpose of the matrix – to give a good overall picture of all the steps involved in the entire process.

3.3 Web Application Development

The possibility to have a site which can be easily modified and developed further in the future was one of the main goals of the project. This requirement affected how the site needed to be built and made it technically more challenging. This was one of the main reasons why Drupal was chosen as CMS because it can offer a very robust yet flexible way to create and manage content. This chapter explains the main concepts of the MAAM site building.

3.3.1 Drupal Specific Development

Drupal was chosen as a content management system (CMS) to be used in the development process. Some basic Drupal specific concepts are introduced in this chapter.

Node

A node in Drupal is the generic term for a piece of content on a website. Almost all content types in Drupal are derived from a single base type referred to as a node. If you are familiar with object-oriented programming you can think of a node type as an object and an individual node as an object instance.

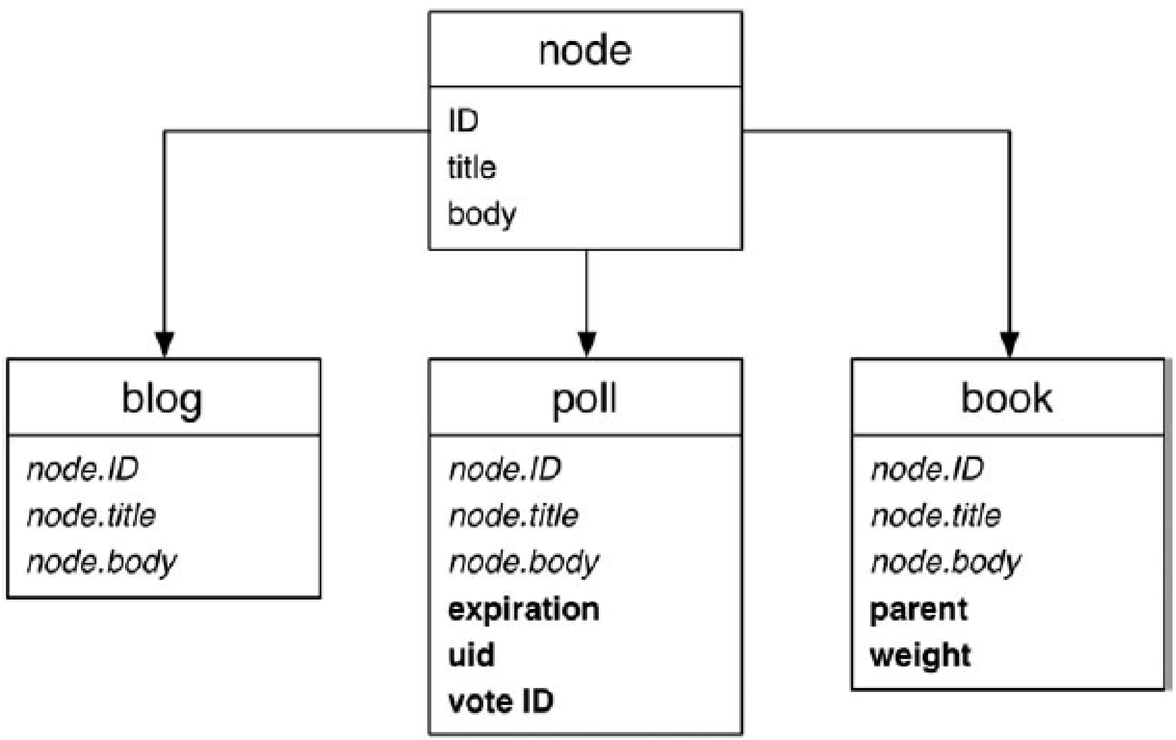


Figure 25: Basic structure and examples of nodes (VanDyk & Westgate 2007)

As you can see from Figure 25, a basic node structure has id, title and body which are inherited to all content types. Whether it is blog entry, MAAM case page, an article page, the underlying data structure of all the nodes is the same. For developers, this means that for many operations, they can treat all content the same programmatically which eases performing batch operations on nodes. Searching, creating and editing become much simpler and straight forward. (VanDyk & Westgate 2007)

Modules and Site Documentation

Drupal is built on a modular structure meaning that developers can add functionality to the website by installing custom modules to the framework. Different modules can carry out different tasks, for example, a module called 'Forum Access' controls which users are able to act as moderators in the forums. Core modules are modules that come with Drupal 6.22 installation and they are the basic building blocks on which a customized website is built upon.

Appendix I: Core Modules is a list of core modules that are used in the MAAM website. The list gives you the name of the module, version number and a description. In the description also the dependencies between modules are shown.

Custom modules are programmed by members of the Drupal community and everyone in the community can use them in their own applications, free of charge. Quite a few custom modules were used in MAAM site. A complete list of enabled custom modules can be found in Appendix II: Custom Modules.

Custom Code

The idea of using a modular structure, on which users can build their custom modules and share them with the community, is great. However, there is also a drawback to this kind of approach. As developers are not, in many cases anyway, paid for the modules they share with the community, some modules are not maintained very well. This means that Drupal updates might break their code or other custom module that uses same functions can make a module to malfunction. This takes an effort from the developer to patch (fix code) quite regularly and he needs to be aware of the risks of losing functionality when upgrading.

Many custom modules that are used in the MAAM site needed patching and debugging (finding bugs in the code) but these are not listed here as they usually are just a fix on a couple of lines of code. Most of the custom code done by the thesis worker is on the theme layer. Theme layer controls how all the information drawn from the database is presented to the users. Theming a website effectively using Drupal requires knowledge of at least Hypertext Markup Language (HTML), Cascading Style Sheets (CSS) and Hypertext Preprocessor (PHP).

For example, one part of the code generating the matrix layout on a web page, which is seen in Figure 42 (page 62), can be found in Appendix III: Custom Code. The basic idea of the code is that PHP if - else if – else functions check the node object for attributes and their values and carry out tasks depending what values are returned. First it checks how many process flows are present at the case and to which classification they belong to. Then it goes through every step in the process flow. If there are values assigned to a specific step, it colors the cell in the matrix, or displays a picture if there is one for that step. It does this to every process flow. The implementation logic makes it possible to have limitless amount of process flows in the matrix. What this code practically does is that it automates the creation of the matrix layout. The user needs to input only the information about a case and according to that information the matrix layout is produced when the user saves the input form.

The code example in Appendix III: Custom Code shows the logic of creating a MAAM page that has a matrix table with one row, a process flow for 1. Preoperative Models to be specific. The logic of creating all the rows in the matrix is the same, only the variables that are checked differ.

3.3.2 Goals and Implementation

Three main goals, regarding the structure, functionality and outlook of the website, were identified before implementation took place. First, the cases and the basic idea behind the new classification system should be easily understood and every mean should be taken in usability to help this goal. Thus, a good structure for the website and the case page is important. Secondly, content elements in the site have a lot of interconnections between them. These relations should be depicted and made intuitive for the user. Thirdly, the site has users with different content access permissions so a coherent and powerful content access permission system by user roles needs to be created. Lastly, as time goes by and more content is gathered to the site, one should be able to analyze this data and create tools that can use this data to find best practices regarding different technologies used in MAAM cases. This is just an aspect that needs to be kept in mind when creating all the functionalities.

Site Structure

To answer the first goal we can take a look at the site structure. Figure 26 shows a screen capture of the front page and Figure 27 depicts the structure of the site.

Figure 26: Front page of the MAAM site

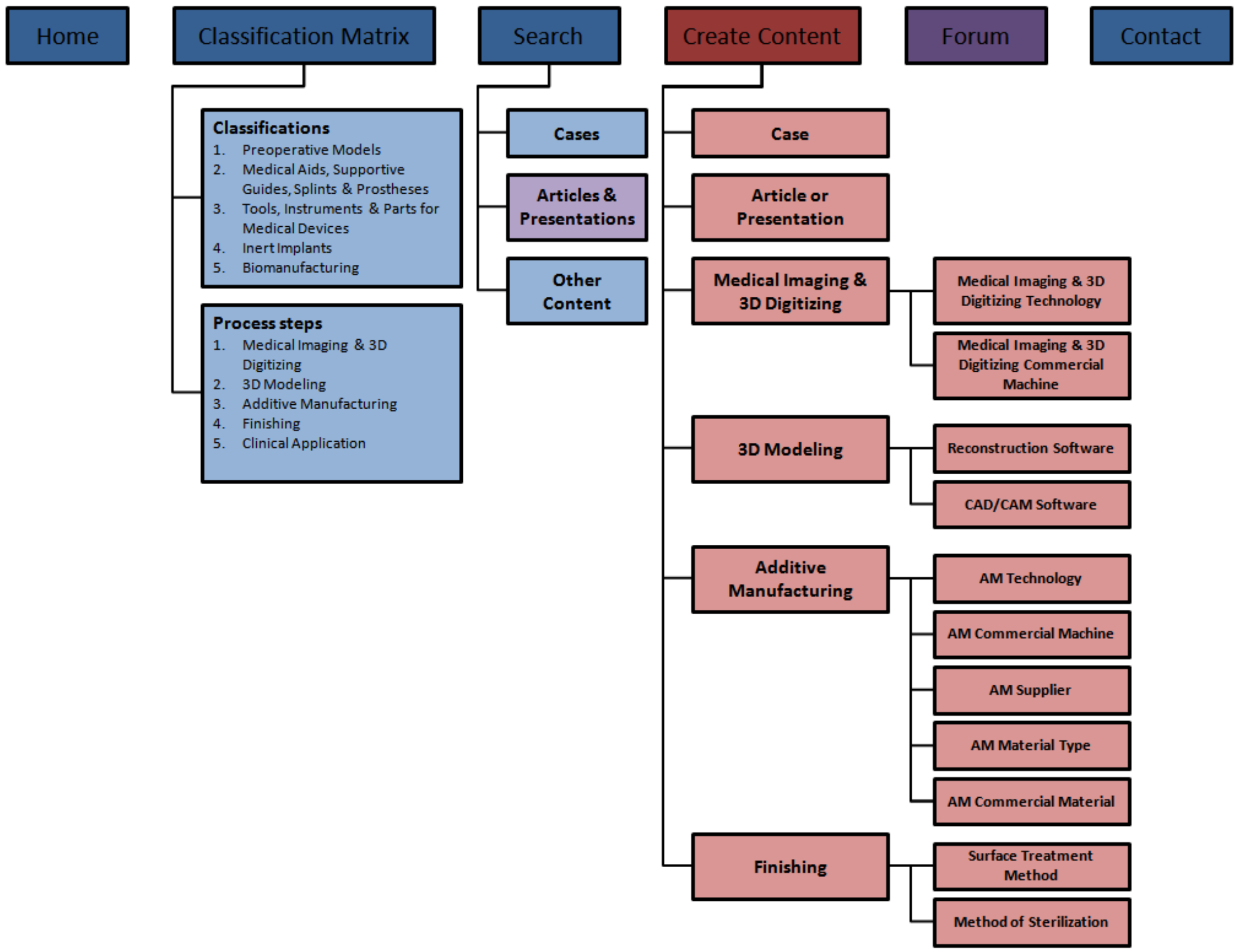


Figure 27: Structure of MAAM site

Home links to front page where all the news and site introductory information will be presented. Classification Matrix links to a page where the user can find detailed information about the classifications and process steps in the matrix. This is where users can go if the matrix seems confusing and they want more information about it. Search is where all the cases, articles and other content can be found. Users can sort and search cases by classification and articles by classifications, keywords, year of publication, authors and free search words. Create content page allows the user to input new content to the site and it is divided into all of the major categories of content in the site. Forum gives the users a chance to discuss about MAAM and other subjects. Contact link has information about how to contact the site administrator if the user has questions. The color coding of Figure 27 represents which kind of user access restrictions there are. This will be covered in the end of this chapter.

From site structure we can move to case page structure. In Figure 28 you can see the structure. On the left there all the content of each block is titled and on the right there is a screen capture from the website. This one page layout has all the information related to one MAAM case. The top part of the page presents the MAAM matrix. The process flows and steps included in the flow are highlighted in blue color or as a picture, if there is a picture available for that process step. Below the matrix there is case specific description, case classification, references, article uploads and contact information of the professionals involved (CAD/CAM professional, AM professional or medical professionals). Under that information are the process flows and all the information stored in subcategories of each process step. These subcategories contain information that was identified as essential information that should be documented in each case. Other case related pictures can be found on the bottom of the page.

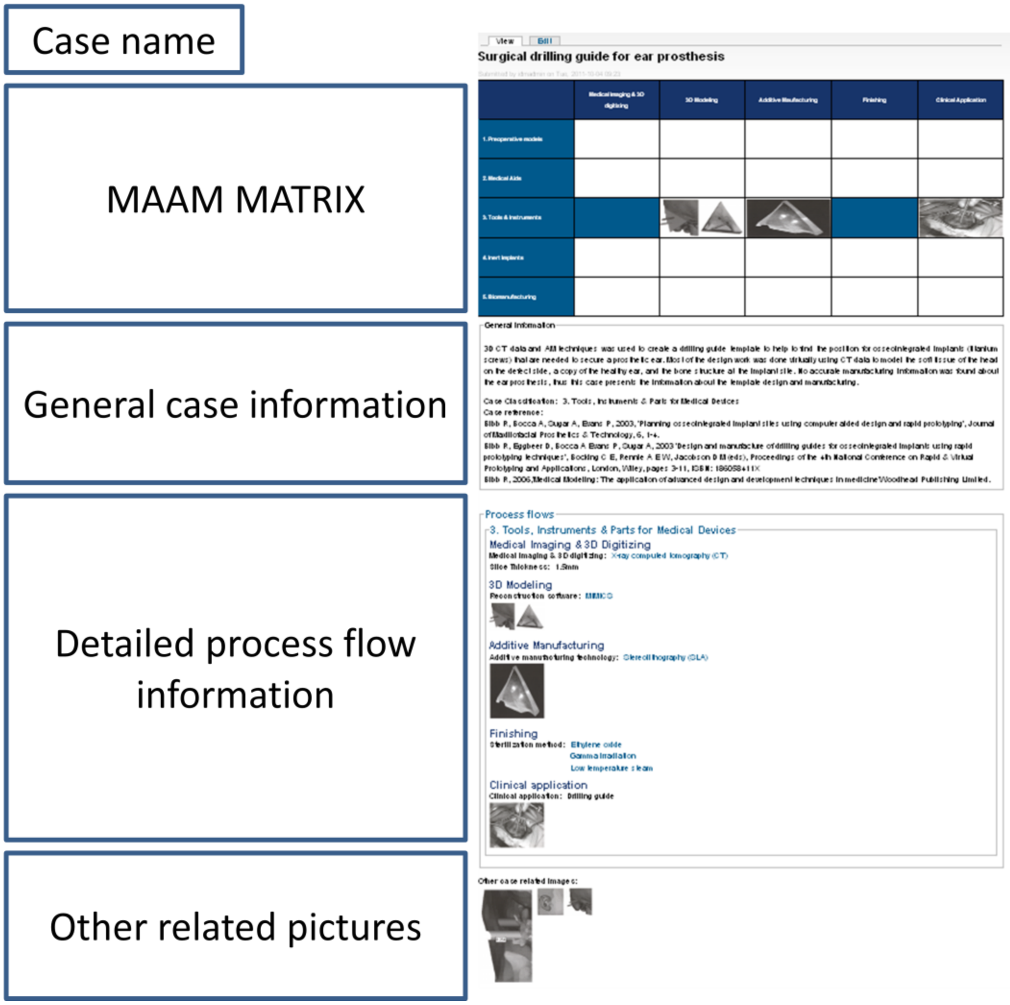


Figure 28: A case view on the MAAM website

According to discussions in the IDM group, this one page layout summarizes well all the important information about each case and presents it in an understandable format.

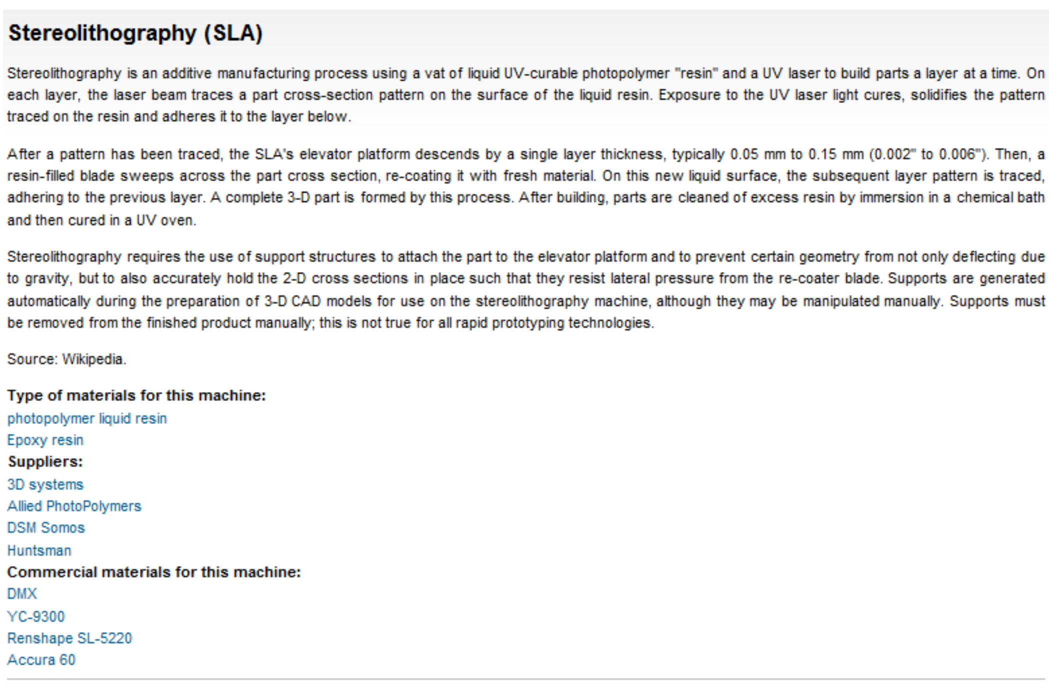
Interconnections of Content

To tackle the second goal, complex database design needed to be implemented. The node system, which was briefly explained in previous chapter, allows to design a system where pieces of content can be connected to each other in logical manner. This action needs Corresponding Node References custom module to be installed and a database table created for storing the reference information between contents.

Figure 29: Close up look of the link in example case

User example: In Figure 28 the user notices that Stereolithography has been used as an AM technology in the case. The user wants to know more about Stereolithography (SLA) and clicks the link on the page. Figure 29 shows the link on the case page.

After the user clicks the link he is directed to a new page. Figure 30 shows the view of the page.



Stereolithography (SLA)

Stereolithography is an additive manufacturing process using a vat of liquid UV-curable photopolymer "resin" and a UV laser to build parts a layer at a time. On each layer, the laser beam traces a part cross-section pattern on the surface of the liquid resin. Exposure to the UV laser light cures, solidifies the pattern traced on the resin and adheres it to the layer below.

After a pattern has been traced, the SLA's elevator platform descends by a single layer thickness, typically 0.05 mm to 0.15 mm (0.002" to 0.006"). Then, a resin-filled blade sweeps across the part cross section, re-coating it with fresh material. On this new liquid surface, the subsequent layer pattern is traced, adhering to the previous layer. A complete 3-D part is formed by this process. After building, parts are cleaned of excess resin by immersion in a chemical bath and then cured in a UV oven.

Stereolithography requires the use of support structures to attach the part to the elevator platform and to prevent certain geometry from not only deflecting due to gravity, but to also accurately hold the 2-D cross sections in place such that they resist lateral pressure from the re-coater blade. Supports are generated automatically during the preparation of 3-D CAD models for use on the stereolithography machine, although they may be manipulated manually. Supports must be removed from the finished product manually; this is not true for all rapid prototyping technologies.

Source: Wikipedia.

Type of materials for this machine:
photopolymer liquid resin
Epoxy resin
Suppliers:
3D systems
Allied PhotoPolymers
DSM Somos
Huntsman
Commercial materials for this machine:
DMX
YC-9300
Renshape SL-5220
Accura 60

Figure 30: A page view of Stereolithography (SLA)

On this page the user is given a brief description of the technology. In addition, under the description, you can notice links to other pieces of content. These links are pieces of content that have been defined to have a connection to stereolithography (SLA). In this case there are connections to type of materials this technology can use, suppliers that offer this technology and commercial materials for it. In other words, the logical connections between machines, suppliers and materials are presented here. The benefit of it to the user is that they have access to other relevant information which will enhance their learning about the subject. All the necessary information about the case is presented on the case page but the reality is that many users are not familiar with all the imaging modalities, AM technologies, materials and so on. They are even less familiar with which materials can be used with specific AM technologies and which companies provide this service. There should be a way for them to access specific information effortlessly from the case page, which this method enables. Figure 31 below gives an overall picture of interconnections in the given example.

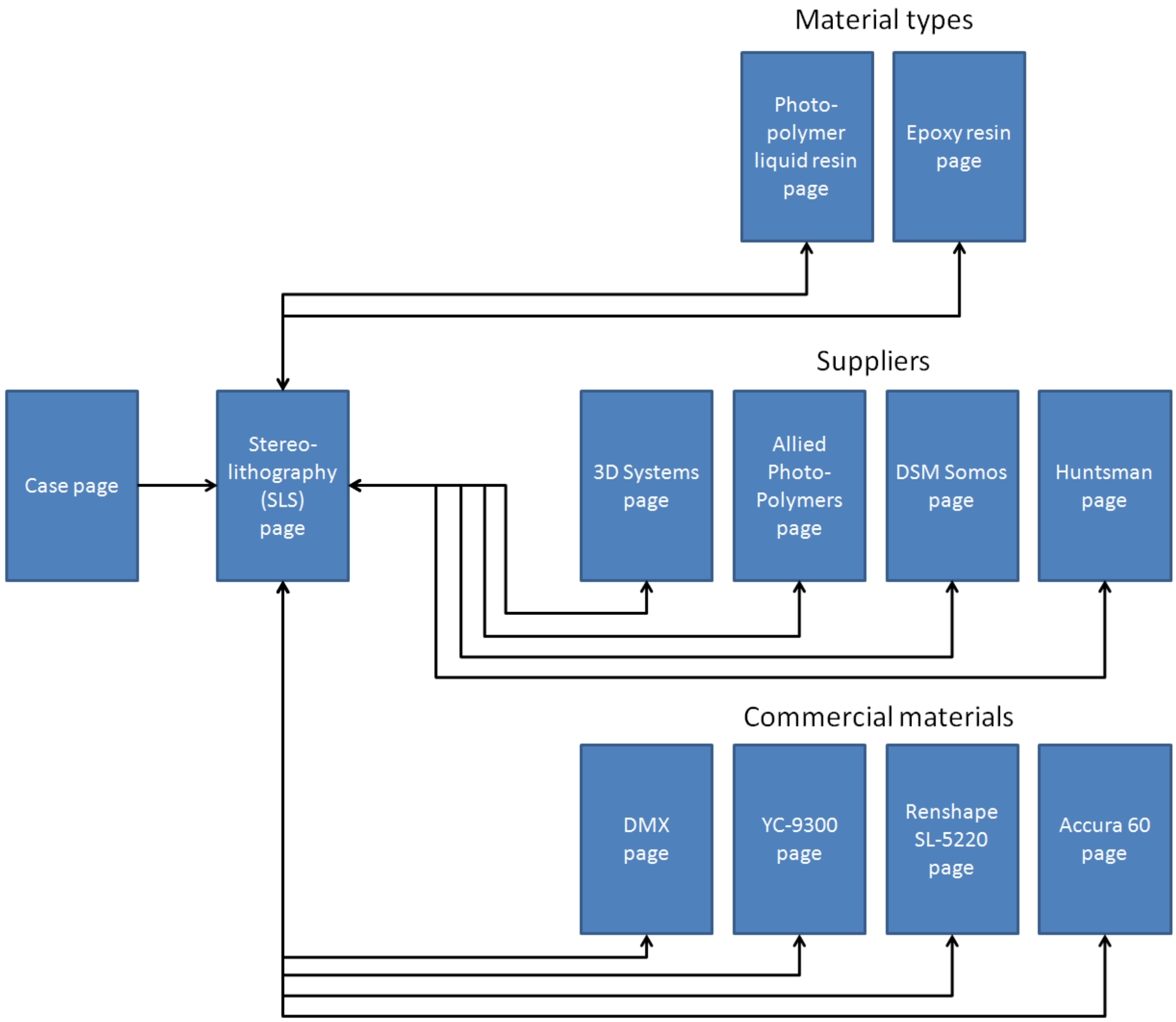


Figure 31: Interconnections of stereolithography

Figure 32 below shows all defined interconnections between content types. This is the logic of which connections to other content types can be made when creating new content to the site.

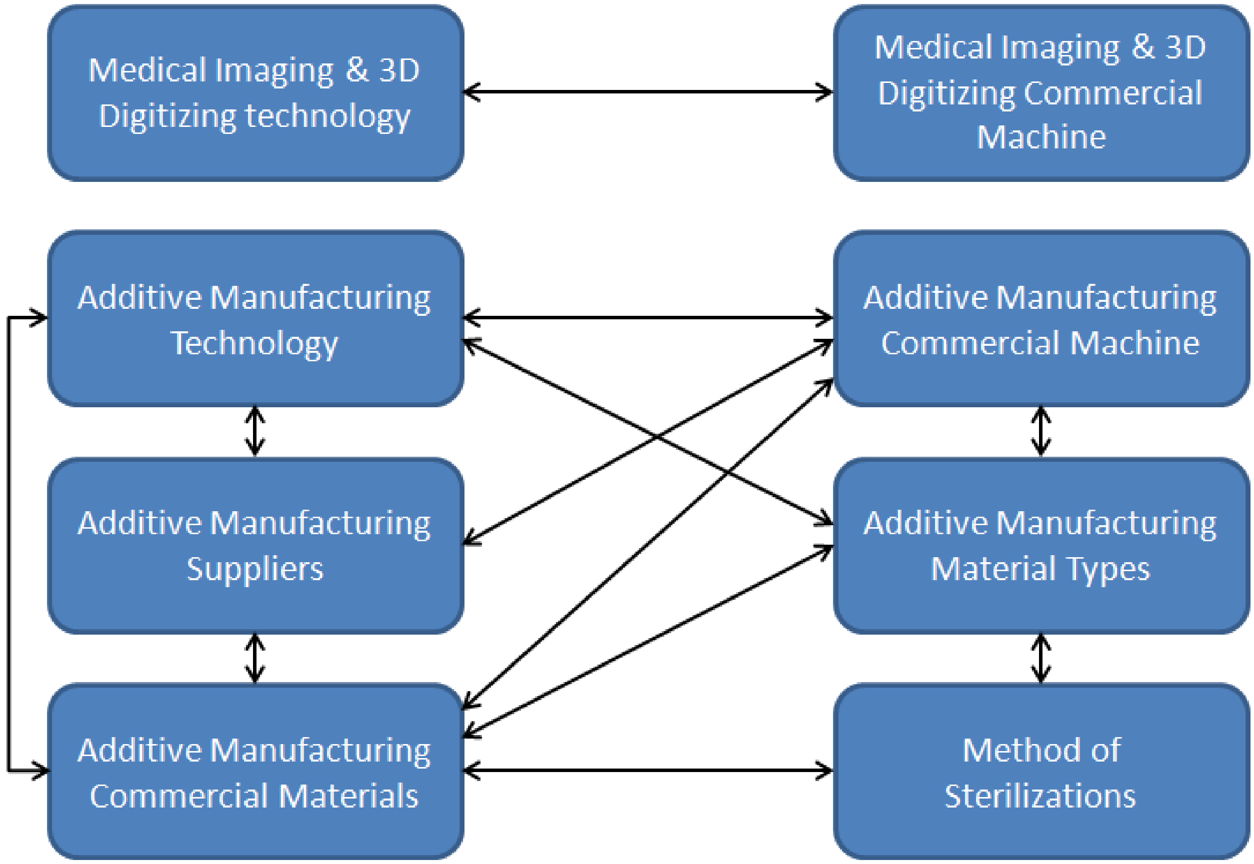


Figure 32: Interconnections between content elements

This functionality is implemented to the system by using Corresponding Node References module and creating a database table that stores information about connections between pieces of content. When an authorized user adds new additive manufacturing technology to the database he/she needs to define the connections also. Figure 33 shows the user interface of adding connections to a new additive manufacturing technology.

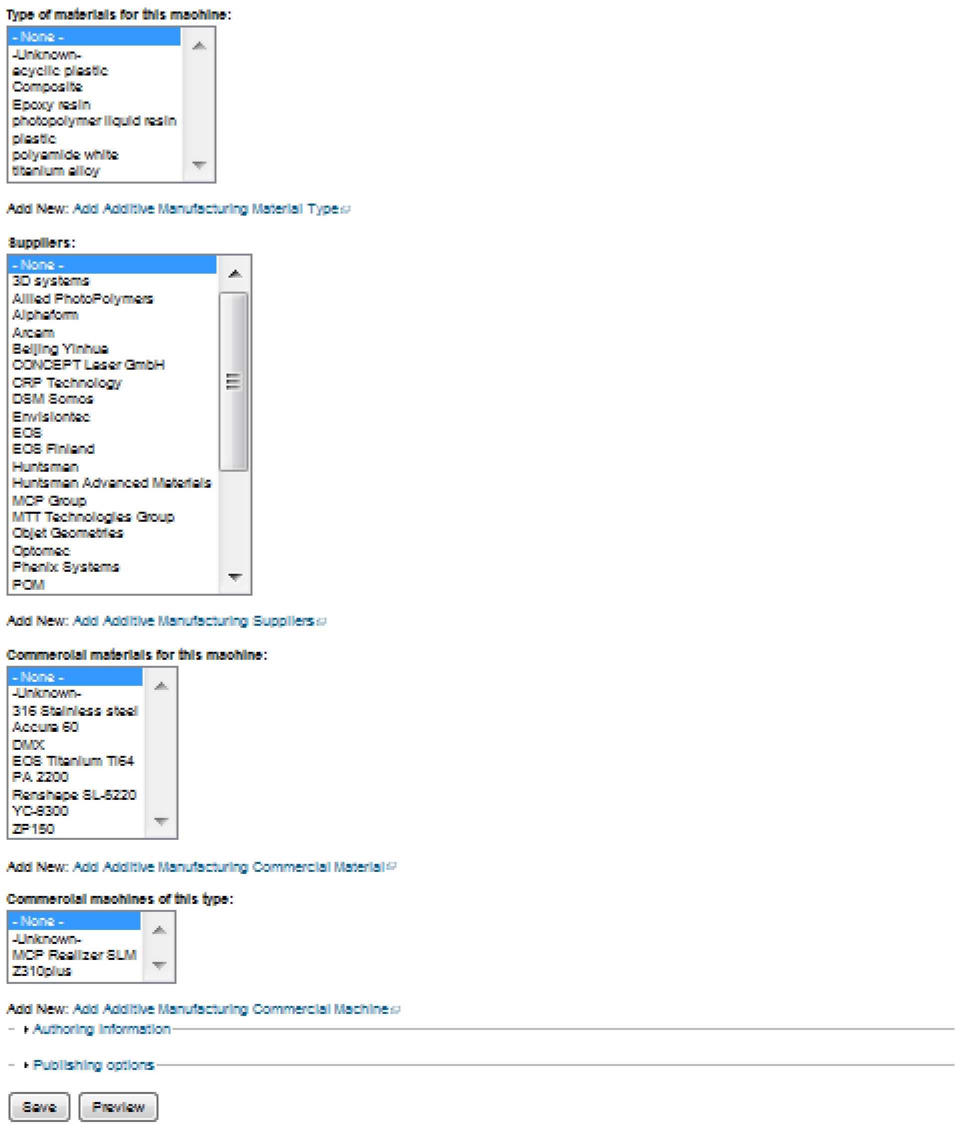


Figure 33: Adding connections to a new piece of content (AM technology in this case)

The benefit of this approach will be best seen in the future when more cases, and thus, more information is stored through the website. Then a user can figure out easily, for example, all the suppliers of a specific AM technology or all the materials that can be used by that technology. This kind of information is not easily available anywhere at this point. Also, managing the connections is not a problem because if a piece of content is deleted from the database also all the related connections are automatically deleted. This will prevent that the site will not have a lot of redundant links.

Creating the connections will of course take an effort from the authorized users who are inputting information. On the other hand, in order to create a website and a collaboration platform that will be recognized globally one needs to have unique information available that brings added value to the users.

User Roles and Restrictions

User roles are an important aspect of the MAAM site. There will be various users in the site and limitations to user groups need to be set in order to keep the site from cluttering of spam messages, useless information and it protects the site from intentional and unintentional sabotage. There are altogether four user roles in MAAM site which are following:

1. Administrator
2. Medaman user
3. Authenticated user
4. Anonymous user

Let's begin with Anonymous user and work our way up. Anonymous user refers to users that are visiting the site but who are not logged in. They have the strictest restrictions and can only view content on the website. If you look at the color coding in Figure 27, Anonymous users can only access sections that are colored blue or purple but not the red section. On blue section they see all the content available but on purple sections there are restrictions. For example, in article search and article pages Anonymous users cannot see pdf-files of articles. On Forum section, Anonymous users can see discussions but are not able to contribute to them.

Next level is Authenticated user. Authenticated user refers to an external user who is registered to the site. At the moment, Authenticated user has the same privileges as Anonymous user, with exception being able to submit comments in the forum. They also receive information about the site, like newsletters, if they wish so. In the future, Authenticated users will get some privileges in content creation but this has to be evaluated when the site has more users. One likely scenario is that Authenticated users can create MAAM cases to the site but in order for these cases to be published they need to go through a screening process where Medaman user or Administrator checks the validity of the case.

Medaman refers to the project 3D MedAman that was introduced in chapter 3.1.1. Medaman user is granted to everyone in the 3D MedAman research team and to collaborators. Figure 27 shows the content creation section in red, which is the section that is restricted from Anonymous users and Authenticated users but access is granted for Medaman users. Medaman user can see all the content in the site and has the capability to create, edit and delete content. Deleting is restricted to one item at a time in order to protect the site from accidental batch deletions. Batch operations, such as deleting many articles or cases at once, are restricted to Administrator. Administrator has the highest user privileges. Administrator can configure anything on the website from source code to content.

These user roles should be sufficient enough to protect the site from many threats and keep the site running well. If new functionalities are designed to the website it has to be decided which users can use those functionalities. As the site develops, there might be a need for new user roles but this should not be in the near future.

4 Validation & Results

4.1 Case Study

I use an example case to illustrate how the process is depicted and how all the case relevant information can be found on the website's case section. The example case is about orbital wall reconstruction by using an orbital implant. This is one of IDM group's medical application cases. First the case is explained thoroughly and then we will look at the layout and structure of the case on the website.

4.1.1 Case Information

A 67-year-old patient had a difficult facial trauma. A patient specific customized 3D model of an implant was designed, a volumetric net formed and several test pieces additive manufactured from stainless steel and titanium. Titanium reconstruction plate was finally additive manufactured and implanted onto injured orbital wall of patient. (Salmi et al. 2011)

Medical Imaging & 3D Digitizing

X-ray computed tomography imaging modality was used to the patient. Tomography images contain information about skin, bones and soft tissue and part of this information is not useful and can be removed by the so called gray scale value method. (Salmi et al. 2011)

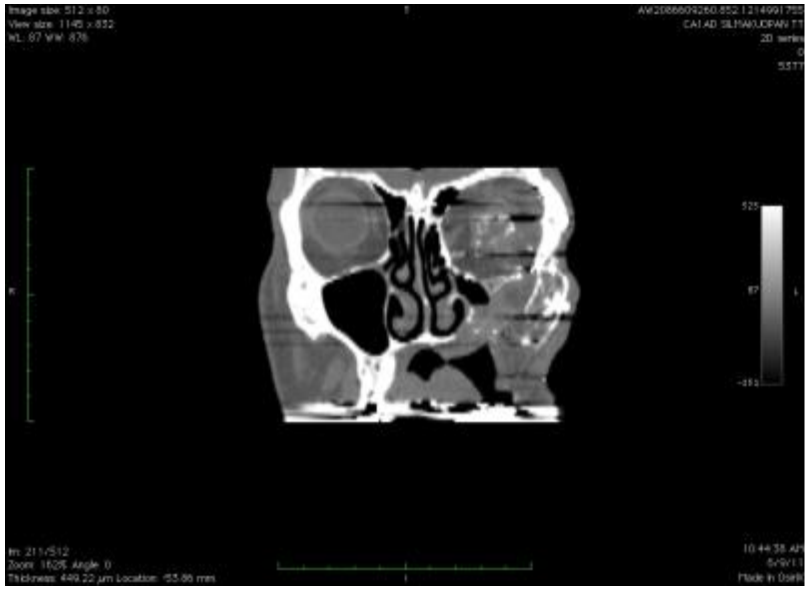


Figure 34: CT picture of patient's orbital wall/head from front.

3D Modeling of the Preoperative Model

A complex and a quick process was needed at the present case so STL interface was used (from optional Medcad and Reverse engineering). First, the medical 3D model of the skull was created from topography images using Osirix 2.7.5 software. The software is based on creating voxels between medical imaging slices. (Salmi et al. 2011)

The corner points of the voxels were examined and based on the corner point's density the surface triangles were made inside voxel. The density value in segmentation was 500 Hounsfield units in order to include bone and objects with higher density to the 3D model. Dental fillings created some artefacts which were cleaned manually. (Salmi et al. 2011)

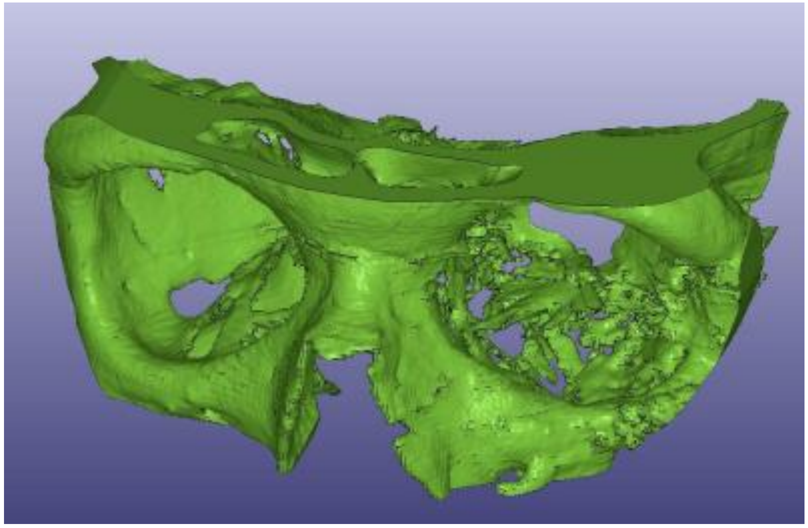


Figure 35: 3D design of the preoperative model

Additive Manufacturing of the Preoperative Model

Additive manufacturing was then used to create a preoperative model of the orbital area and it was created using SLS from fine polyamide 2200. (Salmi et al. 2011)

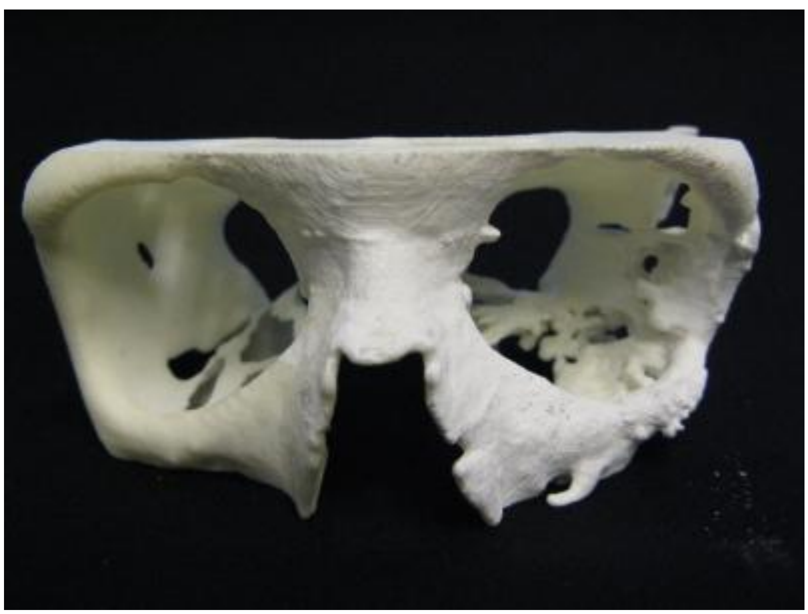


Figure 36: Finished preoperative model

Clinical Application of the Preoperative Model

Additive manufactured model was used in preoperative planning. The surgeon used a marker on the preoperative model to indicate where the orbital implant should be installed. (Salmi et al. 2011)

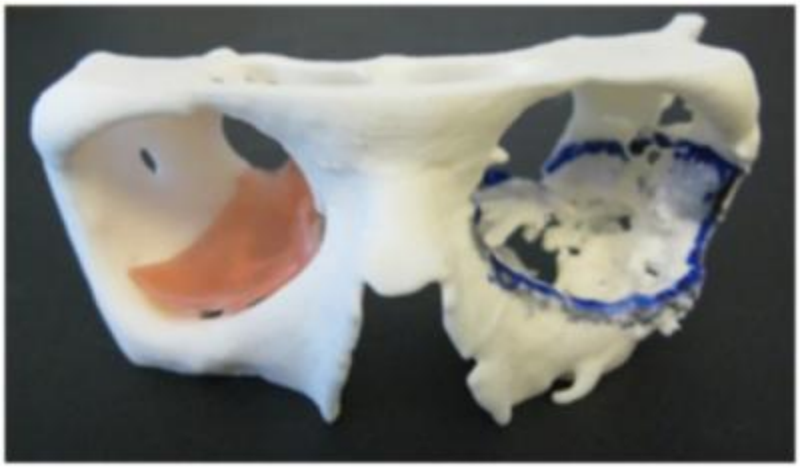


Figure 37: Preoperative model used for surgical planning (Salmi 2009)

3D Modeling of the Implant

The geometry of the orbital implant can be created by mirroring the shape of the facial structure from the opposite side and repositioning it to the actual side. In this case mirroring was used in combination with the surface created from edges of the fractured orbital. Smoothing and adjustment using control points was done and the surface was cut to the correct size. Surface modeling was done using Rhinoceros 2.0 modeling software (McNeel Europe, Spain) and the surface was transferred automatically to the volumetric net macro structure by using 3Data Expert (DeskArtes Oy, Finland). Parameters of the net were 0,4 mm net thickness and 3 mm hole size which are close to those of traditional bendable orbital reconstruction plates. A volumetric network structure was designed to allow tissue and cells to grow through and to/from surrounding tissues and also to reduce sensitivity for fluctuating temperatures. Figure 38 below shows the formation of network structure. (Salmi et al. 2011)

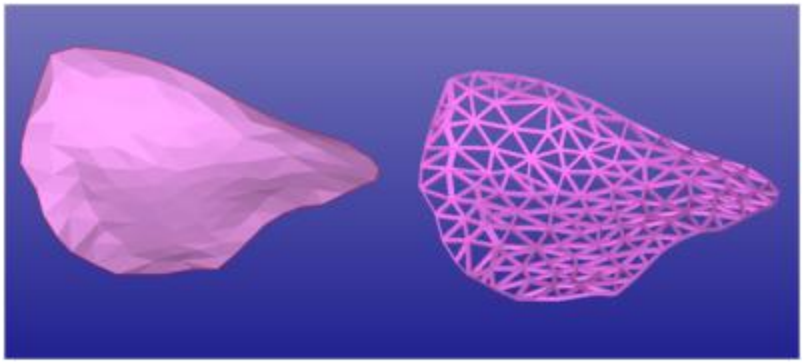


Figure 38: Creating volumetric net from a surface model

The volumetric net (Figure 38) needed a fastening lug which was made by extruding the selected surface after which it was cut to desired shape and attached to volumetric net. The holes for the fastening lug was created using the Boolean operation. Figure 39 shows how the holes were created. (Salmi et al. 2011)

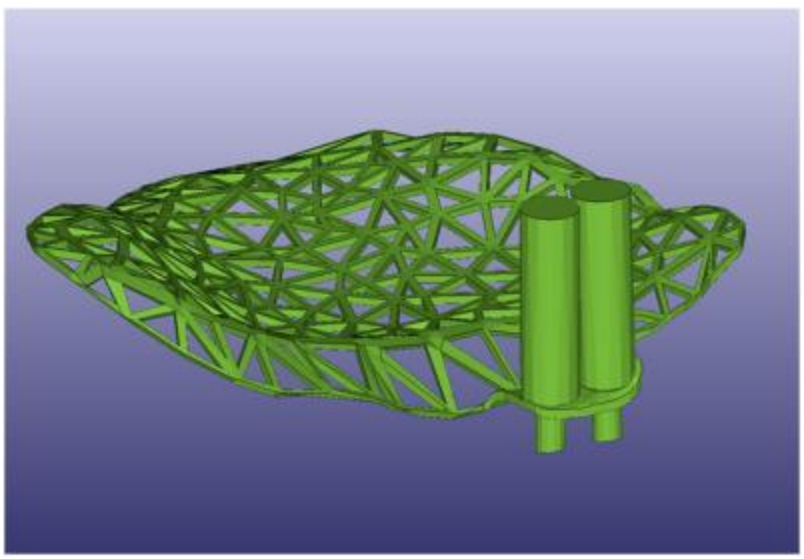


Figure 39: Example of creating holes for screws

After all these operations were done, a finished 3D model was produced.

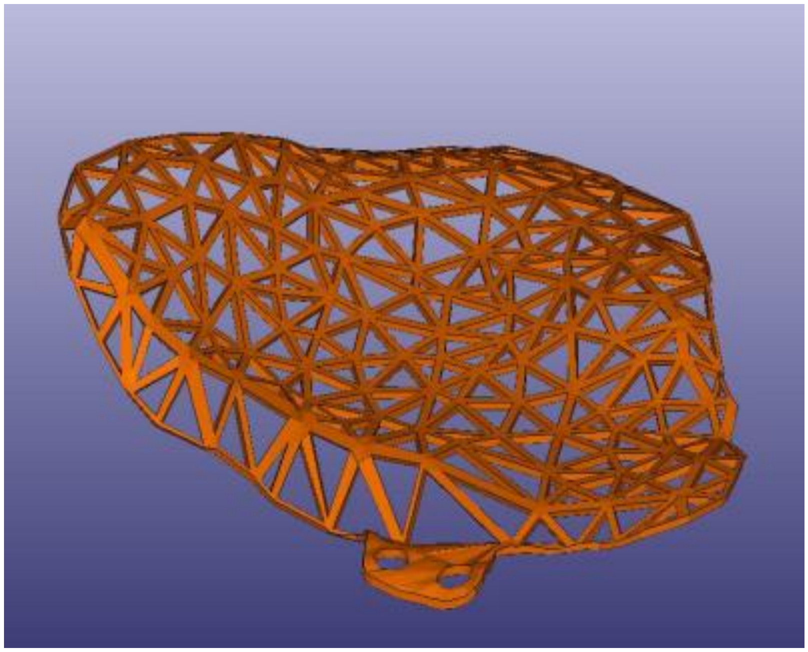


Figure 40: Finished 3D model of orbital implant.

Additive Manufacturing of the Implant

Some prototypes of the implant were manufactured from stainless steel which were used for verification with the preoperative model. The final orbital reconstruction implant was additive manufactured by direct metal laser sintering (DMLS) technology and the used layer thickness was 0.03 mm. The manufacturing system in this case was EOSINT M270 Ti (EOS GmbH, Germany) and the material used was EOS Titanium Ti64 Eli (EOS GmbH, Germany). This material fulfils mechanical and chemical requirements of American Society for Testing and Materials (ASTM) F 136 standard for surgical implant applications. Generally, materials currently suitable for metal implants can be categorized to titanium, titanium alloys and cobalt chrome. Stainless steel and gold are also possible. (Salmi et al. 2011)

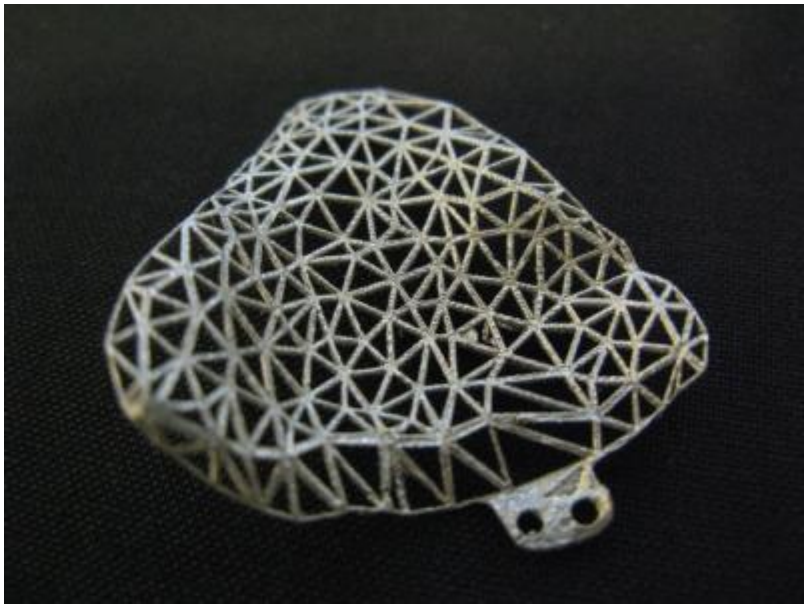


Figure 41: Additive manufactured implant.

Implant Finishing

The implant surface was polished and sterilized. (Salmi et al. 2011)

Clinical Application of the Implant

The orbital reconstruction implant was placed onto the inferior orbital wall and fixed to the bone with two screws. Any external guidance devices were not used and the surgery took about 30 minutes which is 15 minutes less than a traditional reconstruction surgery where the plate needs to be manually bent during operation. The implant fitted precisely and the outcome of the surgery was successful. (Salmi et al. 2011)

4.1.2 Case Modeling on the Website

The idea of the case modeling on the website is to be able to present all the information given in the previous chapter. This should be done in logical one page format that helps the user to understand the production process used in the given case.

The case falls under classification 4. Inert Implants and it has two process flows. First process flow (1. Preoperative models) depicts the design and manufacturing of the preoperative model. This model was used by surgeons to plan how the implant should be designed and how the surgery should be executed. Second process flow (4. Inert Implants) depicts the design and manufacturing of the orbital implant. It is always the end application that defines to which classification a case belongs to. Figure 42 below shows the matrix view on the web page of the case.

Figure 42: Case View of the Orbital Implant Case

Each process step (cell in the matrix) that has information in it is shown in the matrix as a picture or as an area that is colored, if there is no picture available. The pictures depict the end product of each process step. This is where the practicality of the matrix can be well detected. All that information given in the previous chapter is summarized in this matrix and the person who is viewing the case can have quite clear understanding of what has been done just by following the process flows in the matrix.

Process flows

1. Preoperative models

Medical Imaging & 3D Digitizing

Medical Imaging & 3D digitizing: X-ray computed tomography (CT)

Medical imaging & 3D digitizing machines: Philips Brilliance CT 16-slice

Slice Thickness: 1.25mm

Medical Imaging & 3D digitizing description:

Tomography images contain information about skin, bones and soft tissue and part of this information is not useful and can be removed by the so called gray scale value method, which describes the variation of density intensity.

3D Modeling

Reconstruction software: Osirix

HU value: 500

CAD/CAM software: VisCAM

3D modeling description:

A complex and a quick process was needed at the present case so STL interface was used (from optional Medcad and Reverse engineering). First, the medical 3D model of the skull was created from topography images using Osirix 2.7.5 software. The software is based on creating voxels between medical imaging slices. The corner points of the voxels were examined and based on the corner point's density the surface triangles were made inside voxel. The density value in segmentation was 500 Hounsfield units in order to include bone and objects with higher density to the 3D model. Dental fillings created some artefacts which were cleaned manually.

Additive Manufacturing

Additive manufacturing technology: Selective Laser Sintering (SLS)

Additive manufacturing supplier: Alphaform

Type of material: polyamide white

Additive manufacturing commercial material: PA 2200

Additive manufacturing description:

Additive manufacturing was then used to create a preoperative model of the orbital area and it was created using SLS from fine polyamide 2200.

Finishing

Clinical application

Clinical application: Model for surgical planning

Clinical applicaton description:

Additive manufactured model was used in preoperative planning. The surgeon used a marker on the preoperative model to indicate where the orbital implant should be installed.

Figure 43: Detailed information about the preoperative model.

Figure 43 shows all the information available on the creation of the preoperative model. This view is under the 'Professionals involved' area. All process step related parameters and attributes are available and a detailed description about actions in each step is presented.

4. Inert Implants

Medical Imaging & 3D Digitizing

3D Modeling

CAD/CAM software: 3Data Expert
Rhinoceros

3D modeling description:

The geometry of the orbital implant can be created by mirroring the shape of the facial structure from the opposite side and repositioning it to the actual side. In this case mirroring was used in combination with the surface created from edges of the fractured orbital. Smoothing and adjustment using control points was done and the surface was cut to the correct size. Surface modeling was done using Rhinoceros 2.0 modeling software (McNeel Europe, Spain) and the surface was transferred automatically to the volumetric net macro structure by using 3Data Expert (DeskArtes Oy, Finland). Parameters of the net were 0,4 mm net thickness and 3 mm hole size which are close to those of traditional bendable orbital reconstruction plates. A volumetric network structure was designed to allow tissue and cells to grow through and to/from surrounding tissues and also to reduce sensitivity for fluctuating temperatures.

Additive Manufacturing

Additive manufacturing technology: Direct Metal Laser Sintering (DMLS)
Additive manufacturing commercial machine: EOSINT M270
Additive manufacturing supplier: EOS Finland
Type of material: titanium alloy
Additive manufacturing commercial material: EOS Titanium Ti64
Layer thickness: 0.03mm
Additive manufacturing description:

Some prototypes of the implant were manufactured from stainless steel which were used for verification with the preoperative model. The final orbital reconstruction implant was additive manufactured by direct metal laser sintering (DMLS) technology and the used layer thickness was 0.03 mm. The manufacturing system in this case was EOSINT M270 Ti (EOS GmbH, Germany) and the material used was EOS Titanium Ti64 Eli (EOS GmbH, Germany). This material fulfils mechanical and chemical requirements of American Society for Testing and Materials (ASTM) F 136 standard for surgical implant applications. Generally, materials currently suitable for metal implants can be categorized to titanium, titanium alloys and cobalt chrome. Also stainless steel and gold are possible.

Finishing

Method of sterilization: -Unknown-
Finishing description:

The implant surface was polished and sterilized.

Clinical application

Clinical application: Orbital implant
Clinical applicaton description:

The orbital reconstruction implant was placed onto the inferior orbital wall and fixed to the bone with two screws. Any external guidance devices were not used and the surgery took about 30 minutes which is 15 minutes less than a traditional reconstruction surgery where the plate needs to be manually bent during operation. The implant fitted precisely and the outcome of the surgery was successful.

Other case related images:

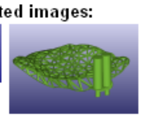


Figure 44: Detailed information about the orbital implant.

The order of the process flows tells the order in which these pieces were manufactured. Figure 44 shows the view on the web page under preoperative model process flow. This view shows all the relevant information in orbital implant design and manufacturing. In addition, other case relevant pictures are found on the bottom of the page.

As of writing, there are altogether 8 cases that have been input to the system. These cases are:

1. Ankle model for surgical training

2. Ankle model for surgical training 2
3. External Ankle support
4. Orbital wall implant
5. Scoliosis
6. Surgical drilling guide for ear prosthesis
7. Creation of titanium orbital floor using a preoperative model
8. Surgical guide for a Le Fort 1 osteotomy

Cases 1-5 are IDM group's own case studies and 6-8 are gathered from external sources. From this case modeling test the experience was that the functionalities in the site are more than sufficient to handle various case types. The problem actually is that for many cases we do not have all the information that we would like to have. This is natural of course because that information has not been documented anywhere. We hope that the matrix and MAAM website will change that in the near future.

4.2 Validation of Matrix structure and Technical Implementation

To validate the solution that was developed during the thesis project the MAAM matrix and the web application was introduced to the 3D MedAMan project members and to the 3D MedAMan project's executive group. In addition, the solution was presented confidentially to Ian Gibson by the research director of IDM group. Ian Gibson is a respected scholar in additive manufacturing field whose articles have been referenced also in this thesis and, moreover, he has many publications of additive manufacturing in the medical context.

Feedbacks from these presentations were mostly positive. The overall structure of the website was received as logical and clear. Especially the matrix structure with pictures in the cells on the case page was given acknowledgment. It was perceived as a good way to get a quick overall picture of MAAM cases. The consensus in all the presentations was that the site has future potential and should be well received by the growing MAAM community.

Most concerns came from the executive group and they were related to intellectual property rights and how to secure information on the website. These aspects need to be taken into consideration when giving more users the right to add and modify content to the website.

4.3 Documentation

The site contains documentation about how it is constructed. All custom code and functions are commented in the code so developers with PHP knowledge can understand how a function is implemented. Appendix I: Core Modules and Appendix II: Custom Modules list all Drupal specific modules that were needed in the implementation. Core modules refer to modules that are offered by the Drupal package and custom modules are the ones offered by the community. These modules form the backbone of many functionalities implemented in the site.

5 Summary & Discussion

In this chapter we look back at the research questions and summarize how this research has answered them and discuss the theoretical and practical contributions this thesis project has made.

5.1 Theoretical Research

The main ***theoretical research question*** was: *What are the critical stages, technologies and attributes in the process that should be depicted?*

The development and manufacturing process of medical applications of additive manufacturing was one key research topics of this thesis. Every step in the process flow was taken into closer look and all the subcategories and critical steps that needed to be documented were examined. The results (process step and its subcategories) of the findings are listed as follows.

Medical Imaging & 3D Digitizing

- Medical imaging & 3D digitizing technology
- Medical imaging & 3D digitizing commercial machine
- Technology specific attributes/parameters

Technology specific attributes for CT and CBCT, which are most commonly used modalities, are slice thickness (mm), voltage (kV), tube current (mAS), overlap (mm), field of view (cm) and matrix size (e.g. 512 x 512).

3D Modeling

- Reconstruction software
- HU (Hounsfield) value
- CAD/CAM software

Additive Manufacturing

- Additive manufacturing technology
- Additive manufacturing commercial machine
- Additive manufacturing supplier
- Type of material
- Commercial material

- Layer thickness

Finishing

- Surface treatment method
- Sterilization method

Clinical Application

- Clinical application

Medical Imaging & 3D Digitizing			3D Modeling			Additive Manufacturing						Finishing		Clinical Application
Medical imaging & 3D digitizing technology	Commercial machines	Attributes/ Parameters	Reconstruction software	HU value	CAD/CAM software	AM technology	AM commercial machine	AM supplier	AM material Type	AM commercial material	Layer thickness	Method of surface treatment	Method of sterilization	Clinical application

Figure 45: MAAM process categories and their subcategories

In addition, also the classifications were studied and the definition and the content of each classification were clarified. Chapter 3.2.1 Classifications discusses this issue in full extent but here is a summarization about the new classifications, their order and a brief explanation.

1. Preoperative models

By using initial data from medical images it is possible to additive manufacture preoperative models. These models can be used in surgical planning, surgical training and to help the surgeon-surgeon and surgeon-patient communication. Depending on the application different qualities of the models such as anatomical accuracy, material characteristics or haptic response of the model become important.

2. Medical aids, supportive guides, splints & prostheses

In this class AM technologies are utilized to enable anatomic personalization of a device or corresponding element. For example, prosthetic sockets can be manufactured using rapid manufacturing technology.

3. Tools, Instruments & parts for medical devices

Additive manufacturing can be used to create tools and hardware for medical applications. This classification includes e.g. operation specific instruments or preforms.

4. Inert implants

Additive manufacturing technologies enable production of very accurate, patient specific implants. The implants are created based on medical imaging data and 3D modeling.

5. Biomanufacturing

Freeform culture media can be manufactured with AM technologies. These applications include biologically compatible parts and scaffolds that can be used as a scaffold for cells. The scaffold acts as a support, protects the cells from external physical forces and provides an optimal medium for 3D culture of cell. Future applications can include AM of tissue and even organ printing.

5.2 Practical Research

The main ***practical research question*** was: *What are the best suitable tools for creating dynamic website for medical applications of additive manufacturing?*

First of all, a website needs a server to run on. A server was built from and old PC that was used as a file server before. I decided to use LAMP stack (a stack of open source software, more specifically Linux, Apache HTTP Server, MySQL and Perl/PHP/Python) because it is quite common bundle of open source software used to build a general purpose web server, thus proven to be applicable for many server needs. Figure 10 depicts the structure of LAMP stack.

Selecting the best technology to build the application layer (top layer on the stack) was not a trivial task. It was not clear from the start if the best choice would be to build the site from scratch by PHP programming or use content management systems (CMS) to provide a framework on which the site would be customized. After studying content management systems more, and having a talk with a web technology expert at the Aalto University, I decided that the best way to advance is to use CMS.

Reasons for the decision:

- CMS speeds up the development process
- Many of them are free of charge
- CMS provides code tested by a community which ensures better site security
- CMS provides a strong framework on which the site can be develop further in the future

After comparing three of the major CMSs (Drupal, Joomla!, Wordpress) I decided to build the site with Drupal. Drupal scored highest in the comparison chart (Figure 12) and it seemed to be the best choice for a highly customized website that might grow in the future.

After the decision was made that Drupal would be the platform on which the site would be built Drupal 7 seemed like an obvious choice. Drupal 7 is the latest version of Drupal that has been released at the time of writing. Usually the latest version of any software is the one that is most developed and secure and should be the standard choice. In this case also I decided to install Drupal 7 for its new features and better future outlook compared to Drupal 6.

After building the site for two months with Drupal 7 I decided to downgrade to Drupal 6. The reason for this was that Drupal 7 was not as stable and well developed as advertised. For some basic functionalities I needed to debug a lot of contributed module. Even with great efforts put to Drupal 7, it seemed that it was still in development phase and would cause even more problems in the near future. The reason for downgrading to Drupal 6, which has been in production use for a couple of years now, was stability and the functionalities it offers. The downside of it is that in couple of years security updates will most likely cease and the site should be upgraded to Drupal 7. By this time Drupal 7 should be quite well developed and upgrading process should not be too big of a task. A lot of customization was also needed on Drupal 6 but in the end it was more stable and thus better choice for this project.

In retrospect, another possible development tool would have been Ruby on Rails (RoR). Ruby on Rails is an open source web application framework that is built on Ruby programming language. With the knowledge gathered in the project, the basic functionalities of the site would have been quicker to implement with RoR. RoR is also more used among my peers in Aalto University so it would have been easier to get feedback and advices for difficult programming problems. Nevertheless, I still think that Drupal was the best choice compared to RoR considering future development of the site. Drupal provides good tools for managing content in the site, even for novice users, and good online community building opportunities.

In the end, a functional web server and a website for inputting and viewing MAAM case data was created. All the basic functionalities that were required were implemented. Usability testing was out of the scope of this research but it would be highly recommended to do some basic usability studies with test subjects to improve the usability of the site.

5.3 Evaluation of the Research

5.3.1 Reliability & Contribution of the Research

Constructive research was chosen as a research method in this thesis project. The constructive approach can be divided into six phases (Kasanen et al 1993):

1. Find a practically relevant problem which also has research potential.
2. Obtain a general and comprehensive understanding of the topic.
3. Innovate, i.e., construct a solution idea.
4. Demonstrate that the solution works.
5. Show the theoretical connections and the research contribution of the solution concept.
6. Examine the scope of applicability of the solution.

Let's examine every phase separately:

1. Practically relevant problem was that MAAM cases had no documentation standard or any correct tools to support documentation. There was a need to understand and depict the MAAM production process more precisely and a framework for this needed to be developed.

2. A general understanding of the additive manufacturing and medical related topics was gathered through literary reviews and team meetings with additive manufacturing specialists and medical specialists. Server building knowledge was gathered from Linux Ubuntu tutorials and from IT personnel at BIT Research Center. Drupal Pro Development books, PHP programming books and the Drupal community forums provided the needed information to build the website with Drupal and PHP coding.

3. After gathering enough knowledge on each topic, the MAAM matrix was constructed to depict the MAAM design and production process and website was developed to promote this framework and bring together professionals in the field.

4. The solution was presented to several additive manufacturing specialists and medical specialists who found it usable and saw future potential for the solution.

5. From research perspective, greatest theoretical contributions were verification of the viability of the matrix model and further study in the process axis. This thesis research deepens the understanding of subcategories in MAAM process, brings together scattered information and makes another step in the direction of using engineering knowhow to aide in medical problems.

On practical side, a documentation standard was built which makes it easier to examine MAAM projects. In other words, a structured, practical approach to discuss about MAAM projects has been created. In addition, now there exists an online platform for MAAM specialist to interact and collaborate. This is first of a kind in this field. There exist some collaborative sites for rapid prototyping with medical sections but they do not have the same kind of case approach. I would argue that the reason those sites have not gained popularity is mainly because there has not been enough interesting content for visitors. We hope that the case selection on MAAM site becomes attractive enough to bring active users to the site. This would bring MAAM forward as a research field and bring more positive coverage.

6. The solution was specifically made for medical applications of additive manufacturing, and therefore, the MAAM matrix and the web application are not applicable in general additive manufacturing context as the classifications and the process steps differ. Otherwise, there should not be a lot of limitations in MAAM context. The scalable nature of the matrix makes it possible to depict all kinds of MAAM cases. Scalability means that one case can have limitless amount of process flows but they all belong to the some of the five classification groups. For example, two different preoperative models might need to be manufactured for surgeon before the operation. This means that the matrix has two process flows in the 1. Preoperative Models classification. The data input system has been constructed in manner that makes this functionality possible on the website.

Even though the matrix is scalable and thus provides a flexible framework to depict cases, it is still in the development phase regarding the process steps. Some classifications might have specific sub processes that would be good to document but for clarity, the process steps are the same for every classification at the moment.

When the MAAM field develops there might come up new classifications or new process steps that need to be taken into account but for now the matrix has been sufficient enough to depict every case that has been tested with it.

5.4 Development Recommendations

Thesis projects are quite small projects after all. This is a reality that had to be taken into consideration when planning the technical implementation. I knew from the start that all the functionalities I wanted to have on the website were not feasible to implement in given time constraints. This was an important thing to bear in mind and understand. For that reason, technical implementation was designed in way that makes it possible to develop the site further with very few limitations.

We can divide the planned development of the MAAM site in three phases.

Phase I: Basic functionalities

Phase one means the implementation that has been done during this thesis project. Technical groundwork has been done. Basic functionalities are in place, which are:

- Information about the classifications and the process steps in matrix format
- Article input and search
- Case input and search
- MAAM related content (AM technologies, suppliers, imaging technologies, etc.) input and search
- Forum for discussions
- Research made for all the important factors in process steps
- Validation of the matrix structure for presenting MAAM cases

In phase I the website serves as an information tool to distribute information about MAAM to medical professionals and engineers. The aim is to make people more aware and get them interested in the potential of MAAM.

Phase II: Enhanced communication, collaboration and productivity

Phase II begins after the site is published. In this stage we should get professionals from different fields involved. They can do this by contributing cases to the system or by acting as contacts that can be consulted by people from the same professional field who are not familiar with MAAM.

This requires a new technological layer to be implemented to the site. Online forum is a good way to engage people in discussions but better ways to get people to collaborate and share their thoughts should be implemented. A way to accomplish this is to build social media layer, or at least, introduce social media functionalities to the site. The scientific community seems to be quite reluctant to adopt social media in their daily work. This can be mainly because they think they are too busy or they just do not see any benefit in it. However, to really make an impact, one needs to build a transparency and dialogue so that the community can build trust and enhance collaboration. For this purpose, taking ideas from social media can be a good way to start building a truly collaborative online community.

Productivity tools should also be implemented at this phase. Productivity tools are technical solutions that help users to present ideas and share material. I have been involved in several project meetings where engineers and doctors have been present. What I have noticed, when attending project meetings, is that visualization increases the level of understanding tremendously between members in a multidisciplinary team. One tool that would enhance the communication would be a virtual 3D model of human. Anatomically correct 3D model that has layers from skin to muscle to bone would enhance communication when discussing a specific part of a body. Tangible, actual models are good for this purpose of course but usually there is not one around when you need it. There are commercial and open source applications available which could be implemented to the site.

To sum up, technical functionalities needed :

- Complex profile system
- Messaging between individual members and groups
- Productivity tools that can be used in team meetings

In this phase more information about MAAM needs to be presented on the site. One difficulty in MAAM field is the multidisciplinary nature of it. Engineers and medical experts do not often speak the same language which can affect negatively the quality of work or willingness to work together. A well documented introductory section of all the professional fields involved in MAAM (radiologists, 3D designers, Additive manufacturing and clinical doctors) and a vocabulary of all central terminology needs to be created. This will enhance learning and lower the threshold of collaboration.

Phase III : Knowledge Based System

The goal in Phase III is to transform the site from a place of information to an online MAAM project management tool. A new layer of functionalities would be built based on the data gathered from a large database of MAAM cases.

At this point the site should have quite a big database of cases and preferably hundreds active users. The idea is to build a service that acts as an online project management tool. For example, when a medical professional decides to have an implant additive manufactured he can contact radiologist, 3D modeling and AM professionals through the website. The medical professional begins a new project through the system and adds all persons involved to that project. This project site will have a knowledge based system implemented which aides the entire team through the production process from medical imaging to clinical application. Some aspects of the implementation:

- Team specific site is automatically created. This is a place where they log on to share information and data.
- Project members have designated roles and tasks
- Files and information are stored to the site and it should be used as a communication platform throughout the project. This way all essential data regarding the project can be found in one place.
- By using this project application the system creates automatically a MAAM case that can be shared with the community if the project team decides to do so.
- The project site has knowledge based system implemented in it

Moura, Bártolo and Almeida (2010) define a knowledge-based-system a computational tool that uses human knowledge and computer power to solve complex decision making problems that normally require human intelligence and expertise. It operates on intelligent system that asks questions and clarifications and guides the user through a decision making process, helping him on the way. There are usually four main levels in a knowledge based system (Moura et al. 2010):

1. User interface, which ranges from a menu driven application to quasi natural-language dialog
2. Knowledge base, which consists all the logic and rules behind problem solving, and the data that is relevant to problem domain
3. Working memory, which refers to task-specific data for the problem under consideration
4. Inference engine, which is a generic control mechanism which generates conclusions from the knowledge base and input data

The long-term goal is to provide a computer-aided decision support tool for each process flow and each process step. For some process steps this might not be needed but Moura, Bártolo and Almeida (2010) argument that an interdisciplinary field like biomanufacturing could benefit a lot from this kind of system. There are many mechanical and biological requirements that need to be taken in consideration when creating an ideal scaffold or implant and a knowledge based system could serve as an automated expert on the matter.

This kind of site could be used globally if we have enough contacts in the database. If a doctor in Italy decides that and additive manufactured preoperative model is needed, he/she can go through the contacts database and find suitable 3D CAD/CAM designers and AM professionals working in the same geographical area. Gathering the contact database should not be an impossible task because having your information there can bring you business opportunities if you are 3D CAD/CAM designer or AM expert. This will of course need a totally different kind of server system that we have implemented at the moment. For that a business model needs to be developed to cover all the costs.

5.5 Topics for Future Research

Apart from technological developments discussed in previous chapter, there is also a need to research the classification specific processes. The general process, which the matrix depicts, is the same for all five classifications but there are, undoubtedly, classification specific sub processes, validation issues, protocols and so on. For example, there are stricter material requirements for implants than for preoperative models. These kind of situation need validation procedures that are not known at the moment.

Other big subject is multidisciplinary collaboration in general. Focus would be between engineers and medical professionals to find out which factors inhibit collaboration and which kind procedures and tools can be used to overcome common obstacles. As medical practice is becoming more and more dependent on computing power and technological solutions, more emphasis needs to be put on how multidisciplinary teams can work efficiently to get best results.

Acronyms

AM – Additive manufacturing

ASTM - American Society for Testing and Materials

CAD – Computed aided design

CAM – Computer aided manufacturing

CMS – Content management system

CSS - Cascading Style Sheets

CT – Computer tomography

CBCT – Cone beam computed tomography

DMLS - Direct metal laser sintering

FDA – Federal Drug Administration

FDM – Fused deposition modeling

GNU GPL – GNU General Public License

GNOME - GNU Network Object Model Environment

HTML - Hypertext Markup Language

HUCH - Helsinki University Central Hospital

JavaScript – A prototype-based scripting language

Linear Attenuation Coefficient - The probability that an X-ray or gamma-ray photon will interact with the material it is traversing per unit path length travelled. It is usually reported in units of cm^{-1} (GE Medcyclopedia 2011)

LAMP Stack – A stack of open source software, more specifically Linux, Apache HTTP Server, MySQL and Perl/PHP/Python which are the components that one needs to build a viable general purpose web server

MAAM – Medical Applications of Additive Manufacturing

MIT - Massachusetts Institute of Technology

MRI – Magnetic Resonance Imaging

PHP - Hypertext Preprocessor

SLA - Stereolithography

SLS - Selective Laser Sintering

STL - Stereolithography file format

TEKES - Teknologian ja innovaatioiden kehittämiskeskus (the Finnish Funding Agency for Technology and Innovation)

3DP – 3D Printing

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Appendix I: Core Modules

Block	6.22	Controls the boxes that are displayed around the main content. Required by: Menu Block (enabled)
Filter	6.22	Handles the filtering of content in preparation for display.
Node	6.22	Allows content to be submitted to the site and displayed on pages.
System	6.22	Handles general site configuration for administrators.
User	6.22	Manages the user registration and login system.
Color	6.22	Allows the user to change the color scheme of certain themes.
Comment	6.22	Allows users to comment on and discuss published content. Required by: Forum (enabled), Tracker (disabled), Forum Access (enabled)
Database logging	6.22	Logs and records system events to the database.
Forum	6.22	Enables threaded discussions about general topics. Depends on: Taxonomy (enabled), Comment (enabled) Required by: Forum Access (enabled)
Help	6.22	Manages the display of online help.
Menu	6.22	Allows administrators to customize the site navigation menu. Required by: Devel (enabled), Hierarchical Select Menu (disabled), Menu Block (enabled), Subsites (enabled), Theme developer (disabled), Subsites Access Control (disabled)
Path	6.22	Allows users to rename URLs. Required by: Global Redirect (disabled), Pathauto (enabled)
PHP filter	6.22	Allows embedded PHP code/snippets to be evaluated.
Profile	6.22	Supports configurable user profiles.
Search	6.22	Enables site-wide keyword searching. Required by: Custom Search (disabled), ReIndex (enabled), Custom Search Blocks (disabled), Custom Search Internationalization (disabled), Custom Search Taxonomy (disabled)
Taxonomy	6.22	Enables the categorization of content. Required by: Content Taxonomy (enabled), Content Taxonomy Autocomplete (enabled), Content Taxonomy Options (enabled), Content Taxonomy Tree (enabled), Custom Search Taxonomy (disabled), Forum (enabled), Hierarchical Select Taxonomy (enabled), Taxonomy Manager (enabled), Taxonomy Menu (enabled), Taxonomy Menu Hierarchy (enabled), Taxonomy Menu Custom Path (enabled), Taxonomy Menu Vocabulary Path (enabled), Forum Access (enabled), Hierarchical Select Content Taxonomy (disabled), Hierarchical Select Taxonomy Views (disabled)
Trigger	6.22	Enables actions to be fired on certain system events, such as when new content is created.

Update status	6.22	Checks the status of available updates for Drupal and your installed modules and themes.
Upload	6.22	Allows users to upload and attach files to content.

Appendix II: Custom Modules

Name	Version	Description
ACL	6.x-1.4	Access control list API. Has no features on its own. Required by: Forum Access (enabled)
Forum Access	6.x-1.5	Allows forums to be set private and allows forums to be given moderators. Depends on: ACL (enabled), Forum (enabled), Taxonomy (enabled), Comment (enabled)
Administration menu	6.x-1.8	Provides a dropdown menu to most administrative tasks and other common destinations (to users with the proper permissions).
Conditional Fields	6.x-1.1	Content fields and groups visibility based on the values of user defined 'trigger' fields. Depends on: Content (enabled)
Content	6.x-3.x-dev	Allows administrators to define new content types. Required by: Conditional Fields (enabled), Content Copy (enabled), Content Multigroup (enabled), Content Permissions (enabled), Content Taxonomy (enabled), Content Taxonomy Autocomplete (enabled), Content Taxonomy Options (enabled), Content Taxonomy Tree (enabled), Corresponding Node References (enabled), Date (enabled), Date Tools (enabled), Fieldgroup (enabled), FileField (enabled), Flexi Field (enabled), ImageField (enabled), Node Reference (enabled), Nodereference Explorer (enabled), Number (enabled), Option Widgets (enabled), Popups: Add & Reference (enabled), Text (enabled), User Reference (enabled), Back Reference (disabled), FileField Meta (disabled), FlexiField Display Contexts (enabled), FlexiField Fieldgroup Integration (enabled), FlexiField FileField Integration (enabled), Hierarchical Select Content Taxonomy (disabled)
Content Copy	6.x-3.x-dev	Enables ability to import/export field definitions. Depends on: Content (enabled)
Content Multigroup	6.x-3.x-dev	Combine multiple CCK fields into repeating field collections that work in unison. Depends on: Content (enabled), Fieldgroup (enabled)
Content Permissions	6.x-3.x-dev	Set field-level permissions for CCK fields. Depends on: Content (enabled)
Content Taxonomy	6.x-1.0-rc2	Defines a field type for taxonomy terms Depends on: Content (enabled), Taxonomy (enabled) Required by: Content Taxonomy Autocomplete (enabled), Content Taxonomy Options (enabled), Content Taxonomy Tree (enabled), Hierarchical Select Content Taxonomy (disabled)
Content Taxonomy Autocomplete	6.x-1.0-rc2	Defines a autocomplete widget type for content_taxonomy Depends on: Content (enabled), Content Taxonomy (enabled), Taxonomy (enabled)

Content Taxonomy Options	6.x-1.0-rc2	Defines a option widget type for content_taxonomy for selects, radios/checkboxes Depends on: Content (enabled), Content Taxonomy (enabled), Taxonomy (enabled), Option Widgets (enabled)
Content Taxonomy Tree	6.x-1.0-rc2	Defines a dynamic tree widget for Content Taxonomy Depends on: Content (enabled), Content Taxonomy (enabled), Taxonomy (enabled), Taxonomy Manager (enabled)
Fieldgroup	6.x-3.x-dev	Create display groups for CCK fields. Depends on: Content (enabled) Required by: Content Multigroup (enabled), FlexiField Fieldgroup Integration (enabled)
FileField	6.x-3.10	Defines a file field type. Depends on: Content (enabled) Required by: FileField Meta (disabled), FlexiField FileField Integration (enabled), ImageField (enabled)
Flexi Field	6.x-1.x-dev	Defines a field type where each field item can be a combination of fields. Depends on: Content (enabled), AHAH Response (enabled) Required by: FlexiField Display Contexts (enabled), FlexiField Fieldgroup Integration (enabled), FlexiField FileField Integration (enabled)
FlexiField Display Contexts	6.x-1.x-dev	Enables an administrator to setup custom display contexts for flexifields, providing additional display control for the child fields within. Depends on: Flexi Field (enabled), Content (enabled), AHAH Response (enabled)
FlexiField Fieldgroup Integration	6.x-1.x-dev	Enables a field group to be used inside of a flexifield. Depends on: Flexi Field (enabled), Fieldgroup (enabled), Content (enabled), AHAH Response (enabled)
FlexiField FileField Integration	6.x-1.x-dev	Enables a file field to be used inside of a flexifield. Depends on: Flexi Field (enabled), FileField (enabled), Content (enabled), AHAH Response (enabled)
ImageField	6.x-3.10	Defines an image field type. Depends on: Content (enabled), FileField (enabled)
Node Reference	6.x-3.x-dev	Defines a field type for referencing one node from another. Depends on: Content (enabled), Text (enabled), Option Widgets (enabled) Required by: Back Reference (disabled), Corresponding Node References (enabled), Nodereference Explorer (enabled)
Nodereference Explorer	6.x-1.2	Interactive node browser as a nodereference widget Depends on: Content (enabled), Node Reference (enabled), jQuery UI (enabled), Views (enabled), Text (enabled), Option Widgets (enabled)
Number	6.x-3.x-	Defines numeric field types.

	dev	Depends on: Content (enabled)
Option Widgets	6.x-3.x-dev	Defines selection, check box and radio button widgets for text and numeric fields. Depends on: Content (enabled) Required by: Content Taxonomy Options (enabled), Node Reference (enabled), User Reference (enabled), Back Reference (disabled), Corresponding Node References (enabled), Nodereference Explorer (enabled)
Text	6.x-3.x-dev	Defines simple text field types. Depends on: Content (enabled) Required by: Node Reference (enabled), User Reference (enabled), Back Reference (disabled), Corresponding Node References (enabled), Nodereference Explorer (enabled)
User Reference	6.x-3.x-dev	Defines a field type for referencing a user from a node. Depends on: Content (enabled), Text (enabled), Option Widgets (enabled)
Chaos tools	6.x-1.8	A library of helpful tools by Merlin of Chaos. Required by: Bulk Export (disabled), Custom rulesets (disabled), Chaos Tools (CTools) AJAX Example (disabled), Custom content panes (disabled), Chaos Tools (CTools) Plugin Example (disabled), Page manager (enabled), Panels (enabled), Stylizer (disabled), Views content panes (enabled), Panels In-Place Editor (disabled), Mini panels (enabled), Panel nodes (enabled)
Page manager	6.x-1.8	Provides a UI and API to manage pages within the site. Depends on: Chaos tools (enabled) Required by: Chaos Tools (CTools) Plugin Example (disabled)
Views content panes	6.x-1.8	Allows Views content to be used in Panels, Dashboard and other modules which use the CTools Content API. Depends on: Chaos tools (enabled), Views (enabled)
Date	6.x-2.7	Defines CCK date/time fields and widgets. Depends on: Content (enabled), Date API (enabled), Date Timezone (enabled) Required by: Date Tools (enabled)
Date API	6.x-2.7	A Date API that can be used by other modules. Required by: Date (enabled), Date Locale (disabled), Date PHP4 (disabled), Date Popup (disabled), Date Repeat API (disabled), Date Timezone (enabled), Node import (enabled), Date Tools (enabled)
Date Timezone	6.x-2.7	Needed when using Date API. Overrides site and user timezone handling to set timezone names instead of offsets. Depends on: Date API (enabled) Required by: Date (enabled), Date Popup (disabled), Date Tools (enabled)
Date Tools	6.x-2.7	Tools to import and auto-create dates and calendars.

		Depends on: Content (enabled), Date (enabled), Date API (enabled), Date Timezone (enabled)
Devel	6.x-1.26	Various blocks, pages, and functions for developers. Depends on: Menu (enabled) Required by: Theme developer (disabled)
Drupal for Firebug Preprocessor	6.x-1.4	A helper extension for the Drupal for Firebug Firefox extension to do preprocessing of forms Required by: Drupal for Firebug (disabled)
Node import	6.x-1.1	Allows users to import node content from a CSV or TSV file. Depends on: Date API (enabled)
Hierarchical Select	6.x-3.7	Simplifies the selection of one or multiple items in a hierarchical tree. Required by: Hierarchical Select Content Taxonomy (disabled), Hierarchical Select Flat List (disabled), Hierarchical Select Menu (disabled), Hierarchical Select Small Hierarchy (disabled), Hierarchical Select Taxonomy (enabled), Hierarchical Select Taxonomy Views (disabled)
Hierarchical Select Taxonomy	6.x-3.7	Use Hierarchical Select for Taxonomy. Depends on: Hierarchical Select (enabled), Taxonomy (enabled) Required by: Hierarchical Select Content Taxonomy (disabled), Hierarchical Select Taxonomy Views (disabled)
ImageAPI	6.x-1.10	ImageAPI supporting multiple toolkits. Required by: ImageCache (enabled), ImageCache UI (enabled)
ImageAPI GD2	6.x-1.10	Uses PHP's built-in GD2 image processing support.
ImageAPI ImageMagick	6.x-1.10	Command Line ImageMagick support.
ImageCache	6.x-2.0-beta12	Dynamic image manipulator and cache. Depends on: ImageAPI (enabled) Required by: ImageCache UI (enabled)
ImageCache UI	6.x-2.0-beta12	ImageCache User Interface. Depends on: ImageCache (enabled), ImageAPI (enabled)
Advanced help	6.x-1.2	Allow advanced help and documentation. Required by: Chaos Tools (CTools) Plugin Example (disabled), Advanced help example (enabled)
Advanced help example	6.x-1.2	A example help module to demonstrate the advanced help module. Depends on: Advanced help (enabled)
AHAH Page Storage	6.x-1.1	Provides a way for modules to store information about the state of a page as it changes during AHAH callbacks. Required by: AHAH Script Ensurer (enabled), AHAH Style Ensurer (enabled)
AHAH Response	6.x-1.2	Provides a themehook to allow for greater control of the response object sent by modules implementing an AHAH callback.

		Required by: AHAH Script Ensurer (enabled), AHAH Style Ensurer (enabled), Flexi Field (enabled), FlexiField Display Contexts (enabled), FlexiField Fieldgroup Integration (enabled), FlexiField FileField Integration (enabled)
AHAH Script Ensurer	6.x-1.0	Ensures that additional javascript files needed by content retrieved using AHAH get loaded. Depends on: jQuery AOP (enabled), AHAH Page Storage (enabled), AHAH Response (enabled)
AHAH Style Ensurer	6.x-1.0	Ensures that additional css files needed by content retrieved using AHAH get loaded. Depends on: jQuery AOP (enabled), AHAH Page Storage (enabled), AHAH Response (enabled)
Corresponding Node References	6.x-4.1	Syncs the node reference between two node types which have a nodereference to each other. Depends on: Content (enabled), Node Reference (enabled), Text (enabled), Option Widgets (enabled)
Custom Breadcrumbs	6.x-1.5	Allows administrators to define custom breadcrumb trails for each node type.
jQuery AOP	6.x-1.0	Adds the jQuery AOP (Aspect Oriented Programming) plugin to all pages. Required by: AHAH Script Ensurer (enabled), AHAH Style Ensurer (enabled)
Maxlength	6.x-2.0-beta2	Set a maximum length for body fields.
Node Export	6.x-2.24	Allows users to export a node and the import into another Drupal installation. Required by: Node Export Files (enabled)
Menu Block	6.x-2.4	Provides configurable blocks of menu items. Depends on: Block (enabled), Menu (enabled)
Node Export Files	6.x-2.24	Export helper module for handling files (CCK FileField, Upload, and Image). Depends on: Node Export (enabled)
Page Title	6.x-2.3	Enhanced control over the page title (in the <head> tag). Depends on: Token (enabled)
Pathauto	6.x-2.0-rc2	Provides a mechanism for modules to automatically generate aliases for the content they manage. Depends on: Path (enabled), Token (enabled)
ReIndex	6.x-1.x-dev	Interactively Reindex the search index Depends on: Search (enabled)
Subsites	6.x-1.4	Subsites are a part of your website that can have its own menu, theme, custom CSS or anything else you want. Depends on: Menu (enabled) Required by: Subsites Access Control (disabled)

Taxonomy Manager	6.x-2.2	Tool for administrating taxonomy terms. Depends on: Taxonomy (enabled) Required by: Content Taxonomy Tree (enabled)
Token	6.x-1.16	Provides a shared API for replacement of textual placeholders with actual data. Required by: Page Title (enabled), Pathauto (enabled), TokenSTARTER (enabled), Token actions (enabled)
Token actions	6.x-1.16	Provides enhanced versions of core Drupal actions using the Token module. Depends on: Token (enabled)
TokenSTARTER	6.x-1.16	Provides additional tokens and a base on which to build your own tokens. Depends on: Token (enabled)
Panel nodes	6.x-3.9	Create nodes that are divided into areas with selectable content. Depends on: Panels (enabled), Chaos tools (enabled)
Panels	6.x-3.9	Core Panels display functions; provides no external UI, at least one other Panels module should be enabled. Depends on: Chaos tools (enabled) Required by: Chaos Tools (CTools) Plugin Example (disabled), Panels In-Place Editor (disabled), Mini panels (enabled), Panel nodes (enabled)
Taxonomy Menu	6.x-2.9	Adds links to taxonomy terms to a menu. Depends on: Taxonomy (enabled) Required by: Taxonomy Menu Hierarchy (enabled), Taxonomy Menu Custom Path (enabled), Taxonomy Menu Vocabulary Path (enabled)
Taxonomy Menu Custom Path	6.x-2.9	Enables Custom path base to Taxonomy Menu. Depends on: Taxonomy (enabled), Taxonomy Menu (enabled)
Taxonomy Menu Hierarchy	6.x-2.9	Enables Hierarchy path to Taxonomy Menu. Depends on: Taxonomy (enabled), Taxonomy Menu (enabled)
Taxonomy Menu Vocabulary Path	6.x-2.9	Enables a custom path for each vocabulary through Taxonomy Menu. Depends on: Taxonomy (enabled), Taxonomy Menu (enabled)
jQuery UI	6.x-1.5	Provides the jQuery UI plug-in to other Drupal modules. Required by: Nodereference Explorer (enabled), Panels In-Place Editor (disabled)
Popups API	6.x-2.0-alpha6	General dialog creation utilities Required by: Popups: Administration Links (disabled), Popups: Add & Reference (enabled), Popups: Test Page (enabled)
Popups: Add & Reference	6.x-2.0-alpha1	In-place popup to add a new node to Node Reference widget. Depends on: Popups API (enabled), Content (enabled)
Popups: Test Page	6.x-2.0-alpha6	Test the Popups API. Depends on: Popups API (enabled)

Better Exposed Filters	6.x-3.0-beta1	Allow the use of checkboxes or radio buttons for exposed Views filters Depends on: Views (enabled)
Views	6.x-3.0-alpha3	Create customized lists and queries from your database. Required by: Better Exposed Filters (enabled), Hierarchical Select Taxonomy Views (disabled), Nodereference Explorer (enabled), Views Bulk Operations (enabled), Views content panes (enabled), Views Custom Field (enabled), Views exporter (enabled), Views UI (enabled)
Views Bulk Operations	6.x-1.12	Exposes new Views style 'Bulk Operations' for selecting multiple nodes and applying operations on them. Depends on: Views (enabled)
Views Custom Field	6.x-1.0	Provides a number of custom fields (rownumber, phpcode, ...). Depends on: Views (enabled)
Views exporter	6.x-3.0-alpha3	Allows exporting multiple views at once. Depends on: Views (enabled)
Views UI	6.x-3.0-alpha3	Administrative interface to views. Without this module, you cannot create or edit your views. Depends on: Views (enabled)
Webform	6.x-3.11	Enables the creation of forms and questionnaires.
noderefcreate	6.x-1.0	create a node when the reference does not exist

Appendix III: Custom Code

```
<?php
// $Id: node.tpl.php
?>

  <div class="node<?php if ($sticky) { print " sticky"; } ?><?php if (!$status) { print " node-
unpublished"; } ?>">
    <?php if ($picture) {
      print $picture;
    }?>
    <?php if ($page == 0) { ?><h2 class="title"><a href="<?php print $node_url; ?>"><?php print
$title; ?></a></h2><?php }; ?>
    <?php if ($submitted): ?><span class="submitted"><?php print $submitted; ?></span><?php
endif; ?>

<?php
//Checks how many process flows there and saves the number in $flowcount variable
  $flowcount = 0;
    for ($b=0; !empty($field_process_steps[$b]); $b++) {
  $flowcount++;
}?>

<!--Draws the colums of MAAM matrix-->
<table class="matrix td" border="1">
<tr>
<td scope="empty"></td>
<th scope="col"><a href="?q=content/medical-imaging-3d-digitizing-0" target="_blank">Medical
Imaging & 3D digitizing</a></th>
<th scope="col"><a href="?q=content/3d-modeling" target="_blank">3D Modeling</a></th>
<th scope="col"><a href="?q=content/additive-manufacturing" target="_blank">Additive
Maufacturing</a></th>
<th scope="col"><a href="?q=content/finishing" target="_blank">Finishing</a></th>
<th scope="col"><a href="?q=content/clinical-application" target="_blank">Clinical
Application</a></th>
</tr>
```

```php
<?php
//This PHP code generates the rest of the MAAM matrix. While loop makes sure that all the process
//flows are drawn.
  $counter = 0;
  $break_while = 0;
    while ( $counter < $flowcount){
     //If-statement checks if process classification value is "6" (Preoperative models). If it
     //is, it proceeds to check each step and assigns "hasvalue" (and a picture if available) for
     //that cell, otherwise it draws just an empty cell.
        if($field_process_steps[$counter]['value']
        ['field_process_classification'][0]['value'] == 6) {
           echo '<tr><th scope="row"><a href="?q=content/classification-matrix"
           target="_blank">1. Preoperative models</a></th>';
           //Check if there is a picture available for this process step and insert it to the cell
           if(!empty($field_process_steps[$counter]['value']
               ['field_imaging_picture'][0]['uid'])){
              echo '<td scope="hasvalue"><a href="'.$field_process_steps[$counter]
                  ['value']['field_imaging_picture'][0]['filepath'].'"
                  title="'.$field_process_steps[$counter]['value']
                  ['field_imaging_picture'][0]['data']['title'].'"> <img class="matrix"
                  src="'.$field_process_steps[$counter]['value']['field_imaging_picture']
                  [0]['filepath'].'"></td>'; }
           //if there is no picture present, check if there are values in the step and if true,
           //color the cell
          else if(!empty($field_process_steps[$counter]
                    ['value']['field_imaging_3d_digitizing'][0]['nid']) ||
                    !empty($field_process_steps[$counter]['value']['field_imaging_3d_digitizing_mac
                    h'][0]['nid'])) {
             echo '<td scope="hasvalue"></td>';}
        //if the process step is empty and has no values, draw an empty cell
        else {
             echo '<td></td>';}

        //Carry out same operations as above to the next process step in the same classification
        //Only variables differ, otherwise functionality is the same.
        if(!empty($field_process_steps[$counter]['value']
              ['field_3d_modeling_picture'][0]['uid'])){
             echo '<td scope="hasvalue"><a href="'.$field_process_steps[$counter]['value']
                  ['field_3d_modeling_picture'][0]['filepath'].'"
                  title="'.$field_process_steps[$counter]
                  ['value']['field_3d_modeling_picture'][0]['data']['title'].'">
                  <img class="matrix"
                src="'.$field_process_steps[$counter]['value']['field_3d_modeling_picture']
                [0]['filepath'].'" title="'.$field_process_steps[$counter]['value']
                ['field_3d_modeling_picture'][0]['data']['title'].'"/></a></td>'; }
        else if(!empty($field_process_steps[$counter]['value']
                ['field_reconstruction_software'][0]['nid']) ||
                !empty($field_process_steps[$counter]['value']
                ['field_cad_cam_software'][0]['nid'])) {
          echo '<td scope="hasvalue"></td>';}
        else {
          echo '<td></td>';}

        if(!empty($field_process_steps[$counter]['value']['field_am_picture'][0]['uid'])){
          echo '<td scope="hasvalue"><center><a href="'.$field_process_steps[$counter]['value']
                ['field_am_picture'][0]['filepath'].'"title="'.$field_process_steps[$counter]
                ['value']['field_am_picture'][0]['data']['title'].'"><img class="matrix"
                src="'.$field_process_steps[$counter]['value']['field_am_picture'][0]
                ['filepath'].'" title="'.$field_process_steps[$counter]['value']
                ['field_am_picture'][0]['data']['title'].'"/></a></center></td>'; }
        else if(!empty($field_process_steps[$counter]['value']
                ['field_am_technology'][0]['nid']) ||
                !empty($field_process_steps[$counter]['value']
                ['field_am_commercial_machine'][0]['nid']) ||
                !empty($field_process_steps[$counter]['value']['field_am_supplier'][0]['nid']) ||
                !empty($field_process_steps[$counter]['value']['field_material_type'][0]['nid'])
                ||!empty($field_process_steps[$counter]['value']['field_am_commercial_material']
                [0]['nid'])){
          echo '<td scope="hasvalue"></td>';}
```

```
        else {
          echo '<td></td>';}

        if(!empty($field_process_steps[$counter]['value']['field_sterilization_picture']
           [0]['uid'])){
         echo '<td scope="hasvalue"><center><a href="'.$field_process_steps[$counter]['value']
                ['field_sterilization_picture'][0]['filepath'].'"title="'.$field_process_steps
                [$counter]['value']['field_sterilization_picture'][0]['data']['title'].'">
                <img class="matrix" src="'.$field_process_steps[$counter]['value']
                ['field_sterilization_picture'][0]['filepath'].'"
                title="'.$field_process_steps[$counter]['value']['field_sterilization_picture']
                [0]['data']['title'].'"/></a></center></td>'; }
        else if(!empty($field_process_steps[$counter]['value']
                ['field_sterilization_method'][0]['nid'])) {
          echo '<td scope="hasvalue"></td>';}
        else {
          echo '<td></td>';}

        if(!empty($field_process_steps[$counter]['value']['field_clinical_picture']
           [0]['uid'])){
          echo '<td scope="hasvalue"><center><a href="'.$field_process_steps[$counter]
                ['value']['field_clinical_picture'][0]['filepath'].'"
                title="'.$field_process_steps[$counter]['value']['field_clinical_picture']
                [0]['data']['title'].'"><img class="matrix" src="'.$field_process_steps[$counter]
                ['value']['field_clinical_picture'][0]['filepath'].'"title="'.$field_process_steps
                [$counter]['value']['field_clinical_picture'][0]['data']['title'].'"/></a>
                </center></td>'; }

        else if(!empty($field_process_steps[$counter]['value']['field_clinical_application']
                [0]['value'])) {
          echo '<td scope="hasvalue"></td>';}
        else {
          echo '<td></td>';}

        $break_while++;
        }
        $counter++;

      }
      //If the classification requirement does not match (meaning that this
      //classification does not have a process flow), only empty cells are drawn
      if ($break_while == 0){
       echo '<th scope="row"><a href="?q=content/classification-matrix"
            target="_blank">1. Preoperative models</a></th>';
       echo '<td></td>';
       echo '<td></td>';
       echo '<td></td>';
       echo '<td></td>';
       echo '<td></td>';
  }
?>
</tr>

/**Above operations are repeated for each classifications and the rows in the matrix are drawn
according to the returned results. Only difference is that variables that are checked differ, so
no need to present them here. Specific documentation can be found from MAAM folder on the server
if needed.*/

</table>

//Print content to the page
<div class="content"><?php print $content; ?></div>
<div style="clear:both"></div>
<?php if ($links): ?><div class="links"><?php print $links; ?></div>
<?php endif; ?>
</div>
```