Design of a CAD and Rapid Prototyping based production process for porcelain

Bachelor Degree Project in Integrated Product Development
C-Level 22.5 ECTS
Spring term 2008

Delia Villatoro Palomar
Manuel Gil Besi

Supervisors: Gunnar Hansson, Rörstrand Kulturforum AB
            Thomas Johansson, Iittala AB
            Christian Bergman, University of Skövde
Examiner:    Lennart Ljungberg
ABSTRACT

The present work has as aim implementing a CAD and rapid prototyping based production process in a porcelain company. There is considerable interest in ceramic companies in implementing new digital technologies in an old-fashioned industry, where traditional handcraft predominate.

The work is carried out in collaboration with Rörstrand Kulturforum AB, whose current process is analyzed, pointing out strengths and weaknesses, to define where to set the focus and the actions to perform. This analysis goes from early stages of product design to slipcasting clay bodies, the forming process of porcelain that uses plaster moulds.

As a result of this analysis, some alternatives including rapid prototyping and CNC milling techniques are defined and compared to one another. Eventually, the definitive solution features CNC milling as the main prototyping system, shaping the mother moulds out of a polyurethane block. This process skips some initial steps, such as manual modelling and mould casting, resulting saving in the new product development. Anyhow, the new process is yet to be tested in the company’s own environment to fully implement it, regarding to various parameters such as the size of the production and the complexity of the products to be manufactured.
INDEX

Abstract 2
Preface 4
Historical background of the company 5
Problems formulation 5
Analysis of the problems 8
First approach 12
Presentation of RP technique 16
Subtractive rapid prototyping 27
Casting materials 29
3D scanning 32
Solutions 36
  Solution 1. From the CAD to the plaster model/ mould 36
  Solution 2. From the CAD to the mother mould 41
  Solution 3. Changing the silicone 46
  Solution 4. From the CAD to the mother mould, CNC 48
  Solution 5. From the CAD to the plastic moulds 50
Discussion of the solutions 53
Final solution 57
Conclusions 60
References 61
PREFACE

This project was completed between February and June, 2008. The entire work was done at Rörstrand Kulturforum AB facilities, in Lidköping, and at the University of Skövde. Apart from the Bachelor's Degree students, Delia Villatoro Palomar and Manuel Gil Besi, there were other people who played an important role in the development of the project. Some invaluable information on the current operations of the company came from Gunnar Hansson, financial manager, and Kristin Andersson product developer. Göran Fogelqvist also helped in contacting some suppliers for materials. We would like to thank Christian Bergman, the supervisor of the project, who always showed great interest on our progress, and Eiler Karlsson, whose first suggestions helped us constructively from the very beginning.

As the time to complete this project was limited, we limited our work to feasible possibilities, within the current state of the industry, rejecting those which were too new and not commercialised yet, let alone the ones that, although seeming to be too good, were little less than impossible to implement.

The bulk of the time for the project was devoted to research, trying to depict in the most accurate way the state of the art towards porcelain manufacturing, considering all the techniques used in prototyping, both machine-based and traditional. To do so, we used different methods, mainly reading (internet searches, books, engineering journals, scientific articles and patents), receiving feedback by contacting several companies and professionals in various fields and talking with people involved in the production process. All the above information was processed through brainstorming sessions.
HISTORICAL BACKGROUND OF THE COMPANY

Rörstrand is the second oldest porcelain manufacturer in Europe and was founded in 1726. Since that time, the company has uninterruptedly been supplying people with top-drawer porcelain products.

In the past century, the company underwent many changes, the most important being the relocation of the factory from Stockholm to Göteborg and eventually to Lidköping (1936), where they have been manufacturing their products until early 2000's. They also underwent several changes in their ownership, with the Finnish group, Iittala, taking over the company.

In 2005 manufacturing was moved from Lidköping, where products development for Rörstrand remains. Rörstrand Kulturforum AB was founded when the relocation of production was implemented, in order to keep Rörstrand's heritage alive. One of the main aims of this company is to support small scale design and production, especially oriented to developers and craftsmen that cannot access bigger production ranges.

PROBLEM FORMULATION

The main issues of this project will be focused on giving as much information as possible. We will also show what the first approach involved.

Though the problem must be treated as a whole, and an integral solution is required, we will firstly define three different tasks, making it easier to understand the different angles of the situation.

The manufacturing process does not make the production profitable. There are two main reasons for this. On the one hand the production method is old, costly and slow. Porcelain is produced the same way it has been for decades, with a handcraft-wait alternation system. As a
“Design of a CAD and Rapid Prototyping based production process for porcelain”

general idea that will later be explained in more detail, in *figure 2.* “Current Production Method” the current manufacturing process of the company is shown.

![Diagram of production process](image)

On the other hand, Rörstrand's current scope is mainly short run production, especially to attract craftsmen, designers and small developers who come and use their facilities sporadically. This could reactivate production in Lidköping and help keep the tradition of porcelain in Sweden. That is why there is a need for improving the current system. Thus, one of the main aims of the project has been defined.

**The communication** between Rörstrand Kulturforum AB and Iittala's production factories needs to be improved. This is an old problem which exists in every company that has product development and manufacturing areas separate from one another, and Rörstrand is not an exception. As mentioned, they still have some product design and development left in Lidköping, which is mainly drawings and handcraft in their workshop. The problem arises when these drawings of a product are sent to the place where they will be produced in large scale to become an item for the real market. In some cases these drawings are misused, either for a lack of information from the source as a result of misinterpretation by the recipient, thus resulting in products not being produced according to specifications, which means wasting money and time.

**Presentations of new series** of products often involve the creation of a product that will never be sold. These kinds of products are created only for presentation, because they belong to a series
“Design of a CAD and Rapid Prototyping based production process for porcelain”

with which they share a certain design language and they are expected to be there. We can point out the coffee pot as one such product. In spite of not being normally produced, there is a need to create at least one, and this arises a considerable problem, as it means that they have to develop (the same way they do other products) a product which will not give any profit back.

It was the company’s suggestion to research RP (Rapid Prototyping) and related technologies as a solution to the mentioned problems. The implementation of some of these techniques would, in a rapid way, solve some of the deficiencies of the company. However, the enormous widths of this field, with numerous possibilities and different techniques - let alone the perfect integration within the company-, require thorough investigation, procedure definition and further testing.

For this purpose, and to a larger extent, we will analyse the production method of the company in the following section. This will lead to the formulation of some ideas on how to perform our work, as a first approach.

ANALYSIS OF THE PROCESS
The following is an analysis of the way the company works at present. Referring to figure 2, 4 and 7 “Current Production Method”, we see that the first stage is preparing the sketches and drawings. That is the main input from which the product developers in the company start the work and it can be drawings and conceptual sketches from an external source or for a product of the company itself. Secondly, the manual modelling starts (step 1, figure 7), which is done by hand-carving fresh plaster material in a completely traditional way. In this, the skills of the craftsman are the principal factors to influence both the duration of the work and the quality of the model. This is a decisive factor to take into account, as it is much more difficult and time consuming to educate a person into craftsmanship than in CAD-modelling, the former being the result of many years and the latter, of months.

This initial stage implies an interpretation of the drawings when they have not been made by the craftsmen themselves, which can also lead to a waste of time and material if there is any kind of misunderstanding, on the part of the craftsmen, or because of a lack of information in the drawings. Thus, this part of the process turns to be the most time and money consuming, and the major costs are the labour. In the case of Rörstrand this phase involves an investment in money and time that is half the total expense. We focus on this issue more
precisely later, when comparing the cost of the current production method with the cost of the suggested alternatives.

In the subsequent stage, some plaster moulds (step 2, figure 7) are cast out of the first model. These moulds are negatives of the desired shape, and their purpose is to test several parameters for the subsequent porcelain casting (slipcasting), such as amount of plaster for the moulds and the number of parts, amount of clay to cast in them, time for the draining and wall thickness for the clay bodies. These tasks are done quickly, with a low cost in materials, since plaster moulds are very cheap.

The next step is the creation of the mother mould (name given to the model that serves as a pattern). Unlike the first model, this is done in silicone rubber (step 4, figure 7). The process is basically a casting of silicone fluid, mixed with a hardener inside a plaster mould, forming a thin layer of a very smooth, rubber-like surface. The definitive moulds for production will be cast in a box with this model, obtaining the negative an accurate surface (step 5, figure 7). Though this stage is not always necessary (it depends on the complexity of the object to be manufactured, and in the number of moulds that will be cast out of the mother mould), most times they build this silicone model, as this material has some important properties that plaster does not have. Among them, we can count flexibility, which makes it easier for the decasting of the moulds, and the durability. This property is essential, as a life lasting silicone model as opposed to plaster models that resist few castings. The reason for this is the extremely high resistance to humidity of this material, as opposed to plaster, which absorbs water, becoming dimensionally unstable after some time.

Despite all these favourable properties, silicone has a drawback, and that is its price. Comparatively it is more expensive than plaster, which makes this step dear. However, the bigger advantage of not having to make several models balances the extra cost. This step is, anyhow, almost as expensive as the manual modelling and only slightly shorter in time, making it a step to emphasise when defining changes in the whole process.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

After this, the moulds for production are cast and the real porcelain manufacturing starts (step 6, figure 7). The clay is cast in the moulds, and left to stick to the walls to get the proper thickness through the so called process of slipcasting, shown in figure 6. Firstly, the mould absorbs the water of the mix, bringing the particles of clay to the walls. If the shape to produce is hollow, the excess of mix is disposed of (drain casting) when the desired thickness is achieved, otherwise the object becomes solid (solid casting). After demoulding, the clay is left to dry and fired, then glazed, and fired again. This part of the manufacturing does not need to be analysed since it is outside our focus.

Following on this overview of the production, the conclusion is clear. There are two steps involving high costs, both in time and money. The first is the modelling stage, with a big investment in specialised labour, and the other is the mother mould making, which involves a high cost of silicone material and spare time because of the time required for the model to cure. It is on these two stages that the main effort should be focused, trying to search for other solutions that, without involving a big reorganization of the company, may shorten the time to production and to marketing and thus reduce the cost of the development phase.

![Figure 6. Slip casting. SCI](image)

The next figure 7, shows the Current Production Method with real illustration in each step of the process for the sample piece.
Process

1. Manual model
   - Most time consuming (1 week)
   - Most expensive step (40%)

2. Casting
   - Moulds for testing
   - Plaster

3. Casting
   - Preparing the mould for casting the silicone
   - Plaster

4. Pouring
   - Silicone mother mould
   - Most expensive step (50%)
   - 3-4 days

5. Casting
   - Moulds for production
   - Fast
   - Cheap

6. Casting the clay
   - Plaster

7. Final products
   - Glazed and hired

Figure 7. Current process illustrated with real pictures
FIRST APPROACH

As mentioned above, it was the company's desire to research rapid prototyping to find solutions, given that the technologies this comprises have been developing considerably in the last few years, thus becoming an important source of prototypes, tools (Rapid Tooling) and even finished products (Rapid Manufacturing) for the industry. Furthermore, the predictions suggest an over growing tendency in the use of these techniques, FFF (Free Form Fabrication), high-speed CNC-milling and rapid casting tool making, as T. Wohlers (Wohlers Report, 2003) points out.

Following our first analysis, and to standardize our methods and not to focus too narrowly on a certain level of the problem definition, we present the process on the basis of the Black Box Model, as discussed in Nigel Cross' Engineering Design Methods (ed. 94, page 66). Employing this approach there is a constant reconsideration of the level of the problem definition, as it focuses not on the process itself, but on what is to be achieved.

A basic representation of this model is shown in figure 8. There are certain 'inputs' that turn into 'outputs' after passing through the 'black box'. The 'black box' contains all the functions which are necessary for converting the inputs into the outputs. (Source: Engineering Design Methods, Nigel Cross, 92)

![Figure 8. Black box](image)

The advantage of this model is that it broadens the possibilities, and if applied to our investigation, causing us not to focus only in RP technologies, since there could be other options.

The next aspect to define in this model is what the inputs and outputs are, which can be done or
classified as flows of either materials, information or techniques. In our case it is not a difficult task to define them. As we already know our process starts with some sketches/drawings of the product, CAD files or ready-made models, sent by people who want them to be produced. Of course, the output of all this has to be porcelain goods ready to be sold in the market, but as we mentioned previously, our area of investigation does not cover glazing and decorating the product. For this reason we can take the green bodies (greenware, unfired articles coming from the slipcasting process) as our output. *Figure 9* shows the development of our idea.

*Figure 9. Developing the Black Box*

As can be seen in the *figure 9*, what is shown inside the 'black box' is to be broken down into sub-tasks or sub-functions. The developer of the model recognizes that "There is no real objective, systematic way of doing this; the analysis into sub-functions may depend on factors such as the kinds of components available for specific tasks, the necessary or preferred allocations of functions to machines or to human operators, the designer's experience, and so on." Consequently, we are basing our first ideas on the sum of our previous knowledge in the field and some intuitions as a result of discussions with people who are knowledgeable in the field. Next *figure 10*, represents the first general ideas of how to undertake the new processes.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

In a first attempt, we will investigate ways of rapidly manufacturing (whichever technique there might be) porcelain products, that means try to find out if there are commercialised machines that are able to manufacture these clay bodies via FFF processes. The main idea is to shorten the steps in the production of the porcelain goods, and that is why direct manufacturing, unless being extremely expensive, would be the best option. If this turns to be impossible, we would move back one step, where the faster achievement of the moulds for production is the main objective. If unachievable, the same goes for this option, then all the effort will be put on the previous step, the construction of the mother mould. In a more general way, figure 11 shows the whole process with a summary of the possibilities.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Figure 11. First brainstorming

The following section will provide the details of our investigation, giving an overview of the possibilities of the industry for porcelain production, emphasizing on RP technologies (kinds and applications) and properties of the materials involved.
PRESENTATION OF RP TECHNIQUES

The term rapid prototyping (RP) refers to a types of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas to co-workers or customers. In addition, prototypes can be used for design testing. Designers have always utilized prototypes; RP allows them to be made faster and less expensively.

As mentioned previously, RP techniques can also be used to make tooling (referred to as rapid tooling) and even production-quality parts (rapid manufacturing). For small production runs and complicated objects, rapid prototyping is often the best manufacturing process available.

At least six different rapid prototyping techniques are commercially available, each with unique strengths and some weaknesses. A software package "slices" the CAD model into a number of thin (~0.1 mm) layers, which are then built one on top of the other. Rapid prototyping is an "additive" process, combining layers of paper, wax, or plastic to create a solid object. In contrast, most machining processes (milling, drilling, grinding, etc.) are "subtractive" processes that remove material from a solid block. RP’s additive nature allows it to create objects with complicated internal features that cannot be manufactured by other means.

Although several rapid prototyping techniques exist, all employ the following basic five-step process:

1. Create a CAD model of the design
2. Convert the CAD model to STL format
3. Slice the STL file into thin cross-sectional layers
4. Construct the model one layer atop another
5. Clean and finish the model
The main Rapid Prototyping techniques are:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modelling (FDM)
- Laminated Object Manufactured (LOM)
- 3D Printer

**Stereolithography**

Patented in 1986, stereolithography started the rapid prototyping revolution. The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. It uses epoxy or acrylate resin. A low-power highly focused UV laser traces out the first layer, solidifying the model’s cross section while leaving excess areas liquid.

Next, an elevator incrementally lowers the platform into the liquid polymer and the laser keeps on tracing layers atop the previous ones. The model is then placed in an ultraviolet oven for complete curing.

*Figure 12: Schematic diagram of stereolithography. Princeton*

Advantages:

- Highest quality surface and accuracy
- Possibility to build transparent models
- Residual machining possible

Disadvantages:

- Strongly allergy-provoking subjects evolves in case of uncompleted curing
- During curing, changes in dimension can occur
- It is among the most expensive: $180,000- $800,000
We cannot mention any specific case where SLA prototypes have been used in the field of porcelain manufacturing. It is considerably expensive, but gives good results regarding to accuracy and dimensional stability. Being the most widespread of all RP techniques, it is easy to find some RP bureaus to outsource the prototypes. Their role in our process could basically be a mould to cast some flexible material (e.g. Silicone rubber) for making the mother mould. There are some applications outside porcelain manufacturing in which SLA is used to cast such material.

**Laminated Object Manufacturing**

In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools. A first layer is cut, then the platform lowers out of the way and fresh material is advanced. The platform rises to slightly below the previous height, the roller bonds the second layer to the first, and the laser cuts the second layer. This process is repeated as needed to build the part, which will have a wood-like texture. Because the models are made of paper, they must be sealed and finished with paint or varnish to prevent moisture damage.

**Advantages:**
- No shrinking and internal stress
- Cheap materials
- Fast building time

**Disadvantages:**
- Hard to cleanly the support structure
- Risk of dividing into two parts
- Tendency to become softer in wet conditions
Abandoned technique

The main disadvantage this technique has is that it is out of use. It is very rare to find a company that builds prototypes with such machinery. This is mainly because of the softness of the prototypes that need special treatments after being built. Otherwise they easily lose dimensional stability and break apart. This results in LOM not being useful in most fields that might require RP objects.

This contradicts somewhat the fact that there have been some experience with LOM and ceramics manufacturing, and more specifically porcelain products development. There is a variant of the original LOM machine that works with ceramic sheets, being able to build prototypes diverse engineered ceramics, including alumina, zirconia, silicon carbide, aluminum nitride, silicon nitride, aluminum silicates, hydroxyapatite, and various titanates.

Furthermore, there are some cases in which the technique has been used to make pottery, but they remain more as unique experiments and tests than some real close-to-be-commercialised techniques.

One of them was performed by Tavs Jörgensen, expert in industrial ceramic production techniques and researcher on how traditional pottery crafts merge with digital technologies, at the Autonomatic Research cluster, in the UK. In his experiment, called 'Binary pottery project', he made some first models of the jars and dishes to be produced in a LOM machine, but as he acknowledges, the process turned out to be inefficient, CNC machining being the best alternative for such a task. The main purpose of LOM in this operation was the achievement of really unusual aesthetics in the pieces. (Picture of 'Binary pottery project') (Source: Binary tools, Tavs Jörgensen).

Another situation in which the terms LOM and pottery blended was in an experiment carried out at INEGI (Instituto de Engenharia Mecânica e Gestão Industrial), Porto (Portugal). In this case, the researchers used some LOM oversized vacuum epoxy infiltrated and painted prototypes with an 'as ceramic' finishing to subsequently cast plaster moulds. As they point out: “For non-complex geometries, this approach seems to be good enough to change the old methodologies, maintaining the necessity of the skilled experienced technicians.” The surface finishing and wall thickness were good enough for the tooling to be used for mass production. They also used some other approaches with the same technique, concluding that, in a general way, when the prices are fundamental, and
high accuracy is required, the mass production tooling must be performed by finishing with CNC (CAD/CAM) high precision machining. However, they claim some Portuguese companies to be using the above mentioned RP technique as part of the production. (Source: *Rapid Prototyping and Rapid Tooling Applied in Product Development of Ceramic Components*, F. Jorge Lino and others)

![Figure 15. LOM moulding](image1.png) ![Figure 16. LOM model](image2.png) ![Figure 17. LOM simulating porcelain](image3.png)

To conclude with LOM, we have to say that we do not advise using it because of all the above factors. Even if there is an already accepted use of it for porcelain manufacturing, the difficulty of finding a source (machine, RP company...) would make it unfeasible for use. As we will see later on, there are no companies in Sweden providing LOM services. Then, the only alternative would be purchasing a machine of a technique that is almost out of the market.

**Selective Laser Sintering**

Developed by Carl Deckard for his master’s thesis at the University of Texas, selective laser sintering was patented in 1989. The technique, shown in Figure 3, uses a laser beam to selectively fuse powdered materials, such as nylon, elastomer, and metal, into a solid object. Parts are built upon a platform which sits just below the surface in a bin of the heat-fusible powder. A laser traces the pattern of the first layer, sintering it together. The platform is lowered by the height of the next layer and powder is reapplied. This process continues until the part is complete. Excess powder in each layer helps to support the part during the build. SLS machines are produced by DTM of Austin, TX.

![Figure 18. SLS Morread State university](image4.png)
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Advantages:
- Material varieties
- No post-hardening needed and auxiliary support
- Residual machining possible
- Functional parts with the same material as the final product

Disadvantages:
- Large space to house it
- High power consumption
- Poor surface finish about 250 RMS.
- It takes time to cool down before working with it (24h)
- Dimensionally of lower quality than SLA patterns
- Prices: $ 300,000

SLS is not the appropriate technique to use for our purpose for several reasons. It is quite dear yet it does not give a good enough surface finishing. Moreover, the prototypes are porous, requiring a sealing in case of being used in applications where the SLS material would be in contact with water. If used as the mother mould, the prototype would require a much better stability and higher performance than what the technique is able to achieve, as opposed to the silicone mother mould, able to withstand numerous castings. In the case of using it as a mould for casting the previously mentioned mother mould, the main requirement would be, once again, the surface finishing.

**Fused Deposition Modeling**

In this technique, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane. Like a baker decorating a cake, the controlled extrusion head deposits very thin beads of material onto the built platform to form the first layer. The platform is maintained at a lower temperature, so that the thermoplastic quickly hardens. After the platform lowers, the extrusion head deposits a second layer upon the first. Supports are built along the way, fastened to the part either with a second, weaker material or with a perforated junction.

![Figure 19. FDM. Xtrem 3D](image-url)
Materials include ABS (standard and medical grade), elastomer (96 durometer), polycarbonate, polyphenolsulfone, and investment casting wax.

Advantages:
• Residual machining possible
• The model can be produced in various colours
• Minimal wastage
• Easy to remove support structure
• Easy to change material
• Minimal set-up time
• Small space to house the machine

Disadvantages:
• Restricted accuracy
• Slow process
• Unpredictable shrinkage

FDM is definitely not the technique to be used in Rörstrand's process. Firstly, its materials are not flexible, and the accuracy is not the best. The unpredictability of the shrinkage of the parts is a big drawback for parts that should be working as tooling patterns.

3-D Ink-Jet Printing

Ink-Jet Printing refers to an entire class of machines that employ ink-jet technology. The first was 3D Printing (3DP), developed at MIT and licensed to Soligen Corporation, Extrude Hone, and others. The ZCorp 3D printer, produced by Z Corporation of Burlington, MA (www.zcorp.com) is an example of this technology. As shown in Figure 6a, parts are built upon a platform situated in a bin full of powder material. An ink-jet printing head selectively deposits or "prints" a binder fluid to fuse the powder together in the desired areas. Unbound powder remains to support the part. The platform is lowered, more powder added and leveled, and the process repeated. When finished, the green part is then removed from the unbound powder, and excess unbound powder is blown off. Finished parts can be infiltrated with wax, CA glue, or other sealants to improve durability and surface finish. Typical layer thicknesses are in the order of 0.1 mm. This process is very fast, and


produces parts with a slightly grainy surface. ZCorpc
uses two different materials, a starch based powder
(not as strong, but can be burned out, for investment
casting applications) and a ceramic powder.

Figure 20: Schematic diagrams of ink-jet techniques for
different companies.

Advantages:

• Easiest, cheapest and faster
• Enable various coloured models
• No wastage of materials
• Quick green bodies

Disadvantages:

• Fragile models
• Poor surface finish

There is much to say about this technique. Nowadays it is the technique which is developing
faster, gaining a bigger market share within RP techniques every year. Thus, there are some exciting
developments involving porcelain manufacturing. Nevertheless, they are not commercially
available yet. For instance, there are some examples of direct manufacturing of ceramics via RP,
and more specifically clay greenware.

The 'Slip Jet Printer' is an apparatus developed as an experiment by
David Herrold, DePauw University, USA. Briefly, the machine uses a pump to
extrude a heavy clay slip through a nozzle. An object is built up by depositing
layers of clay along a rim. The machine produces geometric shapes from a
combination of functions that include: extrude, offset and twist as well as
lathe forms of the potters wheel. Objects produced by the machine can be
altered and finished using conventional ceramic methods.

Figure 21. Slip Jet
Printer. DAvid Herrold
However the Slip Jet Printer is an analogue device using mechanical methods of control, the idea was inspired by contemporary efforts to produce a three dimensional printing machine that is controlled by a model held digitally in a computer. The “Slip Jet Printer” is conceptually a half step between the potter's wheel and a digital three dimensional printer. This machine introduces mechanical precision and geometric complexity but as a hand powered, analog device, it still fulfills the “hands-on” criteria of craft. It is likely to be improved converting it into a digitally driven device.

Another attempt at direct manufacturing ceramics is being carried out by Heinrich and co-authors, presently trying to produce directly in RP machine tableware ceramic prototypes, but the process is still under development and is only suitable for small prototypes (J. Heinrich, J. Gunster, S. Engler: *L'Industrie Céramique & Vérrière Vol. 977, 2002*).

The fact that in his famous annual worldwide report from 2003 (*Wohlers Report, 2003*), T.Wohlers does not mention any work that uses RP processes and ceramic and plaster moulds for the development of ceramic parts shows how new these attempts are to the field we are dealing with.

Apart from this case, already commercialised techniques like Zcorp's 3D-Printing, use a plaster-based composite to build the models. Though it is possible to rapid prototype the plaster moulds and slip cast in them, the quality is very rough and the material, as it is not common plaster, is expensive. Moreover, the life of the moulds is limited by their low strength. Parts typically have a rough, porous surface not well suited to making silicone tooling. They can be impregnated with a liquid resin such as an epoxy to achieve a smooth finish, but the additional post-processing cost is unattractive for this application. There are also some developments in terms of coatings for Zcorp models, in which Tavs Jorgensen, mentioned above, is involved. Due to the fact that these findings are not fully patented yet, we could not get any further information, but it seems that they have the potential of significantly widening the use of RP in the ceramic and glass industry. MIT’s 3DP laboratory (Massachusetts Institute of Technology) is also involved in several projects aiming at the development of materials for specific applications of 3D-Printing machines.
The clearest case of the use of this technique in a porcelain company is Denby's. It is an international pottery manufacturer that uses Zcorp's machines to make their prototypes in plaster material. They purchased some Zcorp device and they recognized to have improved their times to market and efficiency due to several reasons:

- 2 hours printing instead of ¾ weeks for manual model carving.
- In their case, purchasing the machine was more cost effective than outsourcing the prototypes building.
- Company typically detects manufacturing problems four weeks earlier, resulting in shorter time to market. Problems are solved much earlier.
- New product lines launched in half the time.
- Prototypes enable the use of customer focus groups, resulting in more profitable design decisions reflecting true customer tastes.
- Accurate models better communicate design intent internally, with customers, and with suppliers. Testing of the models both internally and externally.
- Production prototype times reduced by half since properly scaled patterns are printed instead of hand-carved.
- Customers are impressed by Denby’s use of advanced technology like 3D printing, elevating the Denby brand.
- Partners in Portugal and Thailand, in charge of the production have their own 3D printer, which leads to perfect understanding between product designing and production areas.
- Repetitively of the models, as they cost around 10 $ in material consumption and machine working time.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

In Denby's case the use of these RP prototypes remains in early stages of the process, with testing and communicative purposes. Yet it quickens the process because of the improvements it brings, it does not influence the production itself. This approach could be used together with some other improvements later in the process, shortening and improving a big deal the whole flow from designing to marketing.

Erik Adolfsson, Keraminstitutet's expert in Direct Casting and Rapid Prototyping argues that Zcorp's techniques are the ones to use in this market.

To this point, and emphasising this case study, it shows the importance of prototypes, that enable complete design iterations to be undertaken until an optimized design is reached. How this process of iterations and customer involvement works is successfully presented in Campbell and Co-Authors, “Design evolution through customer interaction with functional prototypes”. It argues that “the provision of fully functional prototypes can also act as the catalyst for stimulation of further ideas and development”.

To sum up, we can say that there is no possibility in the market that can create porcelain straight out. This statement has been a constant aspect throughout the whole research, and it is verified by different professionals in the field. In fact, this idea is shared by G.P. Tromans, renowned expert in RP processes, working for the RP Consortium at the facilities of the University of Loughborough. Said Tavs Jørgensen is also of the same opinion, although his work is focused on developing new possibilities in the field. Even so, the incredible easiness of RP machines to build whichever shape you can imagine could be an invaluable help in the development of new porcelain products, with improved and limitless aesthetics.

At this stage, the question arises again with renewed urgency: Is there a way to dramatically improve the porcelain manufacturing process at the company, shortening times to market and making it more cost effective? To answer this question we will have to examine other possibilities, such as subtractive fabrication, which is not, as expected, so much an opposite to additive fabrication, but complementary technology, and other porcelain forming techniques different than slipcasting. The expected process might arise from the blending these and the previously explained RP techniques.
SUBTRACTIVE RAPID PROTOTYPING

This term refers to the use of traditional NC cutting for prototyping purposes. The source of info for making a prototype in a CNC-milling machine is the same than for FFF techniques: CAD and CAM files. Subtractive Rapid Prototyping (SRP) is even a lower cost prototyping and parts manufacturing process than additive techniques, let alone the speed, which in most cases is bigger, and the accuracy, much more precise.

A large drilling/cutting tool is used to shape the model removing large quantities of material. Subsequently finer tools (smaller diameters) take care of the profile, passing over and over until the work is close to be completed. Finally, a small tool is used to provide with a surface finishing in accordance to the required standard. Various size and shape cutters are used depending on the materials and the cutting speed. The capability of the machine is defined by its number of axis. There are machines with 3, 4 and 5 axis, the latter being the most capable, nevertheless requiring deep specialisation in using them.

What is more important, some CNC-milling processes can be somewhat used for ceramics manufacturing. Firstly, we will describe the general advantages and disadvantages of both CNC-milling and RP techniques.

The choice between CNC milling and RP is not easy. Both have their own strengths and weaknesses. In our case, the company's skill base both in terms of IT and conventional modelling/moulding techniques is also crucial. The following are some considerations about them (all in the context of ceramic products development).

CNC pros:
- Very good surface quality
- Lower running cost
- Generally larger build envelope
- Much faster than RP

Figure 25. Raku-tool CNC modelling

Figure 26. Reliefs_3D_fraesen_Fotogravuren_CNC
Possible to make mother moulds directly

CNC cons:
- Demands a more skilled operator
- Limitations to the geometry that can be created

RP pros:
- Very easy to use
- No limitation in geometry that can be created
- Can create functional prototypes (example: teapots that pours)
- Can make very realistic prototypes/mock-ups

RP cons:
- Quite expensive running costs
- Slower
- Limited build envelope, rarely over 250mm squared
- Surface quality not as good as with CNC

SRP machines mill a wider range of materials that cost less and do not require chemicals or post-finishing work. Among these materials there is a group of polyurethane foams, called modelling boards. They all share a number of performance characteristics including: ease of machining, excellent dimensional stability, good edge definition and low levels of residual particles for easy clean-up. They are well-suited mother moulds, producing very stable, dimensionally accurate tools with well-defined edges and surface detail when prepared, handled, and worked properly. In addition, CNC-milling machines can also work with pottery plaster.

There are cases of ceramic companies using such polyurethane boards plus CNC-cutting techniques to build mother moulds in which plaster moulds are subsequently cast. The mentioned properties of the material and the precision of the machines make this option attractive, the easy and quick demoulding after casting being crucial to the process. This way, a considerable amount of time could be saved, as from the CAD data the company could be getting the moulds for production
“Design of a CAD and Rapid Prototyping based production process for porcelain”

in just two steps, avoiding the fairly laborious step of manual modelling and casting the silicone. Moreover, here is a point where traditional craftsmanship and brand-new technologies wave hands, as long as some of these milling boards can be even hand-carved. As a matter of fact, a prepared person in both old and new crafts could create shapes joining the straightness and accuracy of digitally controlled machining and the complexity and “uniqueness” of hand-made products.

The only drawback to this possibility is the fact that it requires specialised people, as big CNC-milling machines are not easy to use. Machining takes skill, creativity and the ability to develop solutions to problems in both an engineering and imaginative way of thinking. From designing tool paths and machining strategies to operating and monitoring the cutting, machining is a work for considerably experienced craftsmen. Investing in this kind of machines would involve an investment in know-how, in human resources who are able to manipulate them. Nevertheless, more and more they are becoming user-friendly, with examples of desktop CNC-machines. In this group of machines we can name Roland MDX series, from Roland Company, that delivers desktop CNC-milling machines. They are at the same time milling centres and scanners, and their prices are easily affordable. The disadvantage is that the working area is limited (x=400 mm, y=400 mm, z=155 mm for the largest machine of the series, with a cost of aprox. 180,000 SEK), but once again the formidable properties of the modelling boards can help fix this problem. These boards can be cut and glued together easily, allowing the user to build a prototype out of several slices milled separately. In a sense, there is no size limitation to the parts you can build.

CASTING MATERIALS

The implementation of digital technologies in the production process does not necessarily mean perfection. The time and effort spent in the 3D-modelling phase, which can turn to be an arduous task if the model is complex, in conjunction with the programming of whatever machines you may use and any post-processing work can change what seems to be an easy automated process into a long laborious work. Therefore we also have to look at smaller, but perhaps more effective changes than just relying on the purchase of a big machine.

One possibility could be changing the casting material for the mother mould. There are some materials that can be cast to make this model instead of silicone. Polyurethane resins are formed, similarly to silicone, by a mix of powder material and a hardener. Their properties and applications
are the same to those of silicone. Both kinds of materials belong to what are called Room Temperature Vulcanization (RTV) rubbers, which means that they cure at room temperature. Generally, there is an equivalence relation between silicone and polyurethane rubbers regarding their application and their properties, and for a same standard the latter are slightly cheaper. There are several commercial names for them, such as RenCast and Raku-PUR.

When it comes to a variation in the material of the moulds for casting the clay, polymeric moulds for pressure slipcasting should be mentioned. The material is normally PMMA. Monomer is mixed with a PMMA powder and water and then the mix is poured in a mother mould, just as if making a plaster mould. The monomer is polymerized (hardened) and the porosity is created by the water. Despite being porous, moulds made of this material have less capillary force than plaster, and external pressure is required to make the mould absorb water efficiently. Channels within the mould for applying air, vacuum and water are also created during the casting process.

Pressure casting is very common today, especially in the field of sanitary porcelain but also in houseware making. It is more efficient than conventional slip casting, with faster casting cycles and less water content after casting.

In more detail, the pressure in these moulds is much higher, in the range of 40 bar, than in normal slipcasting, where it is around 2 bar. This involves faster cycles (consecutive castings are allowed, without the necessity for the moulds to dry) and completely dry parts, that can be immediately post-processed, unlike conventional slipcasting green bodies. Furthermore, the durability of polymeric moulds is also higher, being able to withstand thousands of castings, whereas plaster moulds can be used up to several dozen times.

This technique is experiencing some radically new improvements, with the development of a new material for the moulds that can be CNC worked. This brand new feature is not commercialized yet. It was developed under the project FLEXIFORM, performed mainly by CERAM, British research centre for ceramics, in collaboration with several European companies, Iittala group and Portec (developer of the material) among them. The project underwent all the steps from formulation to testing, and as Graham Small, CERAM's coordinator for the project with whom we corresponded, the technology proved “to work in the demonstration phase but there

Figure 28. RenCast.

Freemansupply
was not sufficient interest from the ceramic manufacturing industry to put it into production in the factories. CERAM is willing to coordinate the implementation of the technology if anyone wants to put it into production. It would involve the following companies: Lippert (developer of the demonstration machine), Portec (producer of the aluminium-epoxi porous material) and Goodalls (company that milled out the shape from the blocks of material).

The Swedish Ceramic Institute (SCI), in Göteborg, possesses a pressure casting machine, a small production unit, suitable for casting pieces up to about 1 dm³ in pre-studies for large-scale pressure casting (Source: www.keram.se/eng/pdf/slam_eng.pdf).

However, the company showed little interest in this industrial process, this being the reason for us not to go further into this possibility. The focus, as stated in the beginning, is to be put in the early stages of the product development.
3D-SCANNING

There is much to say about 3D-Scanners because of the wide variety of scanning systems and their different applications. Rapid Prototyping technology uses 3D-CAD models, but sometimes these models are not created directly in 3D software packages, but come from the scanning of a part, in the form of a cloud of points or a mesh which can be used to develop the virtual model. The contribution of a 3D Scanner in the factory would consist of two main tasks: The first one is to reproduce an object or piece in the computer more easily than manually using a 3D-modelling software to create it with the same features; and the second one is to attract craftsmen that might be interested in manufacturing their previously hand-modelled models. A physical object is always the best way to communicate shapes, purposes and feelings. Thus, the scanner works as a communication device between designers and Rörstrand, and also between the company's development area and the production facilities: an automatic translator of the other's desire into CAD data, ready to be worked through the manufacturing process.

3D Scanners are generally classified, depending on they perform the scanning, as follows:

Contact: These scanners work though physical touch. Although they are very precise, the act of scanning could involve damages or changes of the model if it is delicate, and it is much slower because the arm supporting the probe has to be physically moved. Examples of this type of scanners are the Coordinate Measuring Machines (CMM) and Hand Driven touch probes.

Non-contact: A radiation or light is used to build the model into the computer, where millions of data points are captured. Applying talc powder helps minimize resolution problems because of the environment (darkness, brightness, transparency…).

They are divided in 3 types:

1. White light scanners (Interferometry) use an optical method for measuring physical parts. It obtains measurements of an object by determining changes in the fringe and distortion of a pattern of white light projected on an object.

2. 3D Laser Scanning is a 3D scanning device that uses a laser to reflect off the part and triangulate with a camera lens, allowing the scanner to determine and create XYZ coordinates. The scanner then uses these points to form a 3D digital model of the part.
- **Laser triangulation** is accomplished by projecting a laser line or point onto an object and then capturing its reflection with a sensor located at a known distance from the laser's source. The resulting reflection angle can be interpreted to yield 3D measurements of the part.

- **Time of flight laser scanners** emit a pulse of laser light that is reflected off of the object to be scanned. The resulting reflection is detected with a sensor and the time that elapses between emission and detection yields the distance to the object since the speed of the laser light is precisely known.

- **Phase shift laser scanners** work by comparing the phase shift in the reflected laser light to a standard phase, which is also captured for comparison. This is similar to time of flight detection except that the phase of the reflected laser light further refines the distance detection, similar to the vernier scale on a calliper.

3. Stereo vision based: A method of capturing three dimensional data based only on cameras. An algorithm of stereo vision involves receiving inputs from two or more different cameras oriented at different angles and analyzing the differences between the images to obtain 3D information. This 3D information is easily read as a 3D point cloud.

After a thorough search, we have chosen three of the most representative scanners in the market, from well-known brands. They belong to different ranges in quality and price.

<table>
<thead>
<tr>
<th>Scanner/ Features</th>
<th>ZScanner 700</th>
<th>MicroScribe MX-RSI Laser System</th>
<th>Roland LPX 600</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supplier</strong></td>
<td>ZCorporation</td>
<td>Direct Dimension</td>
<td>Roland</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td>Non-contact, Laser</td>
<td>Contact, digitalized with laser</td>
<td>Non contact, Laser</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>50µm XY,0.1mm Z</td>
<td>±0.015 mm</td>
<td>±0.05 mm</td>
</tr>
<tr>
<td><strong>Size of the machine</strong></td>
<td>160 x 260 x 210 mm</td>
<td>150 mm square</td>
<td>630 [W] x 506 [D] x 761 [H] mm</td>
</tr>
<tr>
<td><strong>Scan area</strong></td>
<td>Total</td>
<td>1270 mm sphere</td>
<td>Rotary scanning: [D]254mm,[H]406.4mm</td>
</tr>
<tr>
<td><strong>Points per second</strong></td>
<td>18 000 measures / s</td>
<td>28000/s</td>
<td>37 mm/sec</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>From 314235 Kr</td>
<td>From 29771 Kr</td>
<td>From 96647Kr</td>
</tr>
</tbody>
</table>

*Figure 30. Scanners*
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Roland LPX 600
MicroScribe G2-RSI Laser System
ZScanner 700

Figure 31. Source: Roland website
Figure 32. Source: Microscribe website
Figure 33. Source: Zcorp’s website

It is certain that Zcorp’s laser scanning systems are much faster and effective than the rest, but at the same time more expensive. Zcorp's scanners are more adequate to make complex figures without size limitation. ZScanner 700 is a portable scanner which is able to take references itself in relation to the part, so establishing a coordinates system is not needed. Microscribe MX uses a flexible articulated arm technology. It belongs to the contact scanners group, which is not as fast and accurate than the previous ones. It is necessary to determine the points to model the part into 3D-CAD. To save this disadvantage MicroScribe digitizers and portable CMMs are joined together with the RSI 3D laser system that compiles data points that appear in real time in the screen of the computer to show where the density of the points should be increased. Then the software aligns the scanned profiles to give as a result an accurate scanned object. Roland LPX scanners are automated 3D scanners at the touch of a button. If the object is not larger than the dimensions shown in the comparison chart, LPX-600 is the one to use, being relatively cheap and easier to use than the others. The rotating table allows the system to quickly scan the objects. Otherwise, we recommend MicroScribe system.¹

Through the figure above, with the main performance characteristics of the scanners and after discussing it with the company, Roland LPX-600 is the chosen solution. It has enough accuracy for objects like the ones being produced at the company, since Zscanner exceeds this point, with a much higher accuracy than needed. The main factor upon which the company decides to choose this scanner is the fact that it is completely automatic. There is no need for monitoring the work, that can even be done outside working times.

¹ Brochures attached in Appendix 1. Scanners
In summary, in the latest years the industry has seen a bigger tendency into the automation of the manufacturing process of porcelain goods than into cutting steps out of it. Major companies have been purchasing either pressure casting machines or slipcasting plants, consisting of rollers and/or conveyors, with automatic filling and robot-based glazing and processing. These machines and chain processes are completely focused on the manufacturing itself (from the mother mould until the clay products ready to be sold, with all the intermediate steps of casting, firing, glazing and so forth), but have little impact on early stages of the product development.

As mentioned previously, there is little investigation specifically focused on adapting RP techniques to porcelain production. Mostly, the influence of RP in ceramics have more to do with engineering materials, with rapid manufacturing of small parts and some other purposes different from our scope. However, the great opportunities rapid prototyping (in the broadest sense of the term, including both additive and subtractive fabrication, and rapid casting) have a way into the world of porcelain fabrication. Apart from some very interesting experiments being performed, which may lead to further developments that might be used in the industry, there are some activities already put into practice that join RP, porcelain and production to market.

In the following section we will use all the information gathered in this study of the State of the Art to define some alternatives to the current process in Rörstrand, that will later be compared with each other and channelled through some decisional techniques to choose the most appropriate one.
SOLUTIONS

SOLUTION 1. FROM THE CAD TO THE PLASTER MODEL/ MOULD

This solution is based on the 3D-Printing technique. It skips the process of making the initial model by hand, which is expensive and takes much time. A rapid prototyping model made of plaster replaces it. In this stage of the process, it is possible to test the model, which is built in CAD and printed, just as it would be done with a hand-modelled prototype, and correct the possible mistakes. When the shape is perfectly clear and the casting with the number of moulds and the channels to pour the slip into the mould is designed, the next stage is making the plaster moulds. This could be made by: a) RP technique, like the part; b) casting plaster, as it is being made nowadays.

Denby pottery is using Zcorp’s printing machines for the first stage of the process, as it is said in a previous section of the report, so we know with certainty that this innovation can be introduced in Rörstrand.

Solution 1 sketch

Figure 34.
Solution 1 sketch
“Design of a CAD and Rapid Prototyping based production process for porcelain”

The first stage of the process currently takes 1 week for manufacturing the first model and it is worth 50% of the whole process. The sequence after having introduced this implementation would be:

1. Scan the model (Optional)
2. Build the 3D-CAD file for the part or/and the moulds ²
3. Test the moulds and the part in order to check if everything works for the final production
4. Use the model for casting the plaster for making moulds
5. Cast the silicone model
6. Create the plaster moulds for production
7. Production

As long as the moulds made via RP are not as hard and accurate as the ones made by casting, the implementation of this technique for making the moulds is merely experimental, as a support for the design of the casting process and as a way to share ideas. Slipcasting with these RP-made moulds is very crude, and the binder of the plaster material tends to dissolve when in contact with water, making the moulds break apart soon. Nowadays, the introduction of the 3D-Printing technique to directly reproduce moulds made of plaster for production is in an early stage.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Direct moulding</td>
<td>- Fragile</td>
</tr>
<tr>
<td>- Shortened production cycle</td>
<td>- Less quality in surface finishing</td>
</tr>
<tr>
<td>- Save time and money</td>
<td>- Low durability of moulds</td>
</tr>
<tr>
<td>- Early testing and corrections</td>
<td>- Less water absorption</td>
</tr>
<tr>
<td></td>
<td>- Size of the parts</td>
</tr>
</tbody>
</table>

B) Casting the plaster:

Although RP is just used in the first step, it shortens the time considerably and at the same time reduces the errors when creating the first model and helps make the changes earlier and more easily.

² 3D CAD-file attached in Appendix 2-1
Introducing this solution does not mean that the process is dramatically reduced comparing to the current one, as there has to be an investment of time in the CAD designing and in the curing and post-processing of the printed part. Anyhow, it can be a complement to some other techniques in order to computerize all the process.

Even if this technique does not revolutionize the process, it perfectly solves one of the other tasks of the project: the one concerning the communication between the factories. Thanks to the use of CAD files (drawings and 3D models), the manual drawings turn to be unnecessary, and the interpretation becomes easier. The best way to know how the final product has to look like is handling a replica of it, instead of thousands of drawings and views with the dimensions, and the best way to achieve that is having a 3D-Printer in the manufacturing facilities.
ZCorporation offers several plaster materials depending on the needs. Appendix 2-1 shows that it is necessary to take into account different parameters due to not all the machines can work with all offered materials. Regarding to our purpose, the chosen material has to be resistant, with good surface finishing...The printed parts are not good enough for being used as a final model, what make necessary to use a composite or infiltrate to improve or tailor the final properties of the models.

In our case the material which fulfils the demands is zp 131. The next table 1 shows that it has the best qualities of surface finishing and toughness. These characteristics make the material the most appropriate within all the zp range.

![Figure 38. Material comparison chart ZCorp](image1)

![Figure 39. Green strength-time graphic. ZCorp](image2)
"Design of a CAD and Rapid Prototyping based production process for porcelain"

**Machines**

The fastest machines within this technique are ZCorp’s. There are several machines that are able to build models in plaster, with differences between them, the size of the working envelope being the most significant. While Z310 can build in a 203x254x203 mm area, the Z510 works with sizes up to 254x365x203 mm. Most of the models of the company (pots, dishes, and decorative goods) can be built with Z310 printer, but the problems come with the moulds, of a bigger size.\(^{3}\)

![ZPrinter 310 Plus](image1.png)

![ZPrinter 450](image2.png)

![Spectrum Z510](image3.png)

*Figure 40. ZCorporation 3D Printer machines*

\(^{3}\) Technical data ZCorporation materials and systems attached in Appendix 2-2
**SOLUTION 2.** Flexible mother mould

In this case, we have thought of the possibility of making the mother mould by means of rapid prototyping.

Some suitable materials for this purpose are epoxies, elastomers, (poly)urethanes and some flexible polymers. The problem is that only flexible polymers and elastomers can be manufactured in RP machines, while the others have to be cast.

From the 3D-CAD file and using Zcorp's elastomer material (Zp15e), a flexible mother mould can be built, with some important advantages, but also considerable drawbacks.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Saves three steps --&gt; saves time</td>
<td>- No testing first model or moulds</td>
</tr>
<tr>
<td>- Faster than manual</td>
<td>- Humidity resistance</td>
</tr>
<tr>
<td>- Accurate</td>
<td>- Durability</td>
</tr>
<tr>
<td></td>
<td>- Size of the part</td>
</tr>
<tr>
<td></td>
<td>- Generally needs coating</td>
</tr>
<tr>
<td></td>
<td>(Por-a-mold) and polishing.</td>
</tr>
</tbody>
</table>

The material being used currently for mother moulding is silicone Elastosil M 4643. It takes about 3 or 4 days to cure and the step of creating the mother mould with it costs around 40 % of the entire process, taking into account the price of the material, the time and the labour. The thickness of the casting is usually 8-10 mm. It is easy to cast silicone because of its high viscosity.

---

3 Elastosil datasheet Appendix 3-1. STL part for this solution Appendix 3-1
and low density. Once cured, the demoulding of the part is easy, since it deforms to let the mould out, yet it recovers the shape.

As an example, we have calculated the price of the mother mould for a specific model, in order to obtain exacts the amount of silicone and money that it costs, so we can compare it with possible solutions. We have constructed the part in 3D with Pro/E software, which has a command that allows you to calculate many parameters, such as volume and weight. This file has been used for these calculations, as well as for getting quotes from companies to which we have sent the model.

The silicone price for this specific model is ~ 2040 Kr. All initials steps should be added which means about:
First model + Plaster moulds for testing: ~ 10000 kr (1000 material + 9000 worker)

The following chart shows some RP materials that might be used in this solution. They belong to different companies in Sweden and abroad, from which we tried to get a quote.

<table>
<thead>
<tr>
<th>Material / Properties</th>
<th>Zp15e</th>
<th>Tango Plus FullCure 930</th>
<th>DuraForm Flex plastic</th>
<th>Somos 9120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>ZCorp</td>
<td>Skaramodellsnickeri</td>
<td>3D System</td>
<td>AME Prototypes</td>
</tr>
<tr>
<td>Technique</td>
<td>3D printer</td>
<td>Polyjet</td>
<td>SLS</td>
<td>SLA</td>
</tr>
<tr>
<td>Base</td>
<td>Cellulose-based powder.</td>
<td>Extremely soft rubber-like</td>
<td>An elastomeric plastic</td>
<td>Epoxy photopolymer</td>
</tr>
<tr>
<td>Characteristics</td>
<td>Rubber-like properties</td>
<td>Used in place of urethane, silicone or rubber parts</td>
<td>- Accurate -Rigid &amp; Functionality -Excellent humidity tolerance</td>
<td></td>
</tr>
</tbody>
</table>

Figure 43

---

5 Volume calculated in Appendix 7-1
Analysing the solutions in depth:

**ZP15e**

General properties:

This material allows the user to create parts with rubber-like properties by means of infiltrating the printed part with an elastomer, called Por-a-Mold. Zp15e absorbs the elastomer and becomes tough and flexible.

Zp15e can be used by ZPrinter 310 and Spectrum 510. The differences between them the binder and the printhead. While Zprinter 310 is using one HP printhead, Z510 uses four, making the printing faster.

The next figure shows a comparison between ZCorp's materials:

![Material Properties Comparison](image)

*Figure 44. Zcorp’s material comparison*

If this becomes the chosen solution the company would have to purchase a Zprinter machine, as we have not found any company supplying parts in the elastomeric material in Sweden. Of course, another possibility is outsourcing it with a company outside Sweden, but in that case there would be more expenses for the delivery.

**Somos 9120**

Somos 9120 produces accurate functional parts ideal for master patterns in rubber applications. In contrast, the technical properties make it not very suitable for our purpose, because of low humidity resistance and lack of dimensional stability. Furthermore, from a quote from AME prototypes, rapid prototyping company in UK, we concluded that this option does not save much money.

---

7 Datasheet reference in Appendix 3-2
Tango Plus, FullCure 930

It is also a rubber like material which is flexible, durable, tough and resistant to tearing and deterioration.

Comparing this material to Elastosil there is some divergence in properties, but they share a long elongation at break. However, it is also very expensive, while it does not assure the same performance as the casting resin.

Duraform Flex plastic

The advantage of this flexible material is that it can be used for end-use parts because of the good surface finishing, even with small parts though the properties are worse than silicone's. Therefore this option can be quickly ruled out.

Estimations

Below is a quote from Amalgam, British company supplying RP prototypes. We contacted them to get a quote for the 3D-CAD file above, to build a flexible mother mould, but their suggestion was to CNC mill a mould to be used to vacuum casting a resin (7150) in it. Although the mother mould is not created via RP, the quote just gives an idea of how expensive it can be.

Figure 46: Part made of Tango Plus. ProtoCam

Datasheets references in Appendix 3-2
It comes about 11800 kr just to the annotated steps. It is not much expensive that the current one, but the disadvantage is that it is not possible to test the first model, which is a very important step for the company, as we will see in the Pugh matrix afterwards.
SOLUTION 3. Replacing the silicone

The idea of this solution is to replace the silicone with a cheaper material, without a loss in properties and performance, reducing the price of this step. As we have already explained, these materials are RTV resins with similar properties to Elastosil, the durability being the most important.
In the market we can find a wide range of polyurethanes for different purposes like abrasion, temperature, oils,…Their machinability makes them to adopt any shape easily.

Alternatives:

- **RenCast series. (Supplier: Abic Kemi AB, Sweden)**

  RenCast is a series of polyurethane resins whose properties are quite close to silicones, but slightly cheaper.
  It was Abic Kemi, the supplier, who recommended RenCast FC 52\(^8\) for our application. It is low viscosity polyurethane with excellent properties compared to RTV silicone. One of its applications is flexible moulding, allowing easy removal of complex parts.
  As it is showed in the Appendix 4-1 all the properties can be compared.

- **Freeman 1040 polyurethane elastomer\(^8\) (Supplier: Freeman, USA)**

  As we said before is an alternative to RTV silicone rubber mold making materials what makes it ideal for plaster casting and prototypes.

- **PU 342 A/B\(^8\) (Supplier: Alchemie, Denmark)**

  PU 342 A/B is another flexible polyurethane resin used for mould making that can also replace Elastosil.
  This Danish company gave us a quote, resulting in a lower price than Elastosil, even when the delivery expenses have to be paid.
  Quote:
  195 Kr/ Kg + 25% VAT + 200 kr (delivery)

\(^8\) Technical datasheet Appendix 4-1
“Design of a CAD and Rapid Prototyping based production process for porcelain”

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Very similar to the silicone</td>
<td>- No automation advantage, it just</td>
</tr>
<tr>
<td>- Cheaper</td>
<td>minimizes the expenditure</td>
</tr>
<tr>
<td>- Complementary used with the rest of solutions</td>
<td></td>
</tr>
</tbody>
</table>

Whereas the rest of the solutions imply some kind of investment, just changing silicone for polyurethane cuts the price of the process. This change of material is more a complementary feature than an integral solution itself, since its incidence is reduced to a mere and slight reduction of the price. It does not cope with the roots of the issue.
SOLUTION 4. CNC

In the same way that it is possible to get moulds via RP, they can be built by milling the shape out of blocks, as it was stated in the section State of the art. This process skips the three first stages and takes us directly to the mother mould.

This option is, as we see it, the most feasible. It was suggested by Tavs Jörgensen. This solution was somewhat depicted in the section mentioned above. The material is low-medium density polyurethane board, that can be milled with a good surface finishing and precise shapes and edges. They can also be hand-carved, being both machining and craftsmanship mixable to get the desired shapes. A commercial brand for this material is RenShape⁹.

![Diagram of Solution 4](image)

*Figure 49. Solution 4 sketch*

There are two sub-options within this alternative. One is building the positive out of the block, as the mother mould's shape, for casting the plaster moulds in the next step. The other would be milling the negative form, to later cast the positive, either in silicone or some other polyurethane casting resin (explained in solution 3) and so get the mother mould. Even plaster could be cast to get a sample model.

⁹Datasheet of RenShape 5460- Appendix 5-1
**Render of the parts- Appendix 5-2
Below is an estimation of the price made upon the modelled file, calculating the amount of material needed (we also wrote down the price of a whole block of the material, that should serve for several works). There is also a quote from Suncab AB (CNC), company located in Lidköping.

**Solution 4**

[Diagram showing the process of 3D-CAD to CNC estimation]

This alternative has many advantages, such as the quickness in the achievement of the mother mould -straight from CAD data- and the low price of the material. There is only one drawback, that after all can also be saved, and it is the problem with negative draft angles. An intelligent design of the casting process, with the right number and a correct definition of the parts of the moulds and some expertise in CAM there should not be any unachievable shape.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Quickness from CAD data to prototype</td>
<td>- Has to be outsourced (investing requires much money and skilled personnel)</td>
</tr>
<tr>
<td>- Saves several steps</td>
<td>- Special considerations with the shape</td>
</tr>
<tr>
<td>- Material workable with both machinery and hands</td>
<td></td>
</tr>
<tr>
<td>- Cheap material</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 50. CNC estimation**

**Figure 51**

- 49 -
SOLUTION 5. To the plastic mould

In this solution the mother mould is built, like in the current process, by casting silicone (or polyurethane resin) in moulds prepared for such purpose. The difference is that, unlike the moulds that are currently made by casting plaster, these ones are made by SLA. The figure below shows the flow of the process.

![Figure 52. Solution 5 sketch](image)

Solution 5

There are several materials that can be used in this solution, all of them belonging to the group of materials with which SLA works.

Here is a list of different materials used in RTV moulding, arranged by company:

3D Systems\(^{10}\)
(SLA)
- Accura 25 plastic
- Duraform PA&GF
- Duraform Flex
- Accura 60
- Accura 25
DSMSomes\textsuperscript{10}

- Accura Xtreme plastic
- Watershed 11122XC for RTV patterns
- 14120 White
- Somos 9120 epoxy

\textbf{Solution 5}

\textbf{Figure 53.} Solution 5 estimation

The \textit{figure 53} shows an estimation of the price this technique would have if trying to create our 3D-model. It becomes expensive as the creation of two moulds is needed. The main problem is that, in order to make it cheaper, the parts have to be shelled out and the thinner the walls, the weaker and less durable the moulds.

\textsuperscript{10}Datasheet Appendix 6-1
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Easiness and rapidity to get the mould for casting the silicone/flexible material</td>
<td>- Mostly expensive</td>
</tr>
<tr>
<td>- It skips the first step which is the most expensive</td>
<td>- Limited size (building in parts becomes extremely expensive)</td>
</tr>
<tr>
<td>- High accuracy in the parts</td>
<td>- Less durability than current mother moulds</td>
</tr>
</tbody>
</table>

*Figure 54*
DISCUSSION OF THE SOLUTIONS

The solutions defined in the previous section need to be discussed and assessed, and in the end one (or a mix of several) of them will be selected as the process to be implemented in the company. For this, and so as to follow a more precise and objective approach, we will use the decision-matrix method, also called concept selection matrix and Pugh's matrix.

Basically, it is a process of narrowing the set of concept alternatives under consideration. As an overview of the methodology, and in a first stage, a matrix with the different concepts to be evaluated is done -in our case this refers to the solutions we have given to the problem-, taking one of them as a reference. For us, the current process will be the axis of coordinates with which all the rest of the concepts will be compared. Consequently, this reference concept will be given points -standard values- for all the criteria involved in the decision-matrix.

Subsequently, points are given to the rest of the concepts accordingly to how they satisfy each criterion in comparison to the reference. Criteria are given a weigh, depending on how relevant they are to the final decision, so as to make it more accurate and objective.

Once all the solutions have been rated, there is a value, result of the sum of the different criteria, that shows what solution is the most appropriate or, at least, clearly enlighten what the strengths and weaknesses of these solutions are. In subsequent stages solutions can be blended to get a more integral solution with the strengths of all the others, covering the weaknesses.

In our case, we presented to the company a matrix with some criteria that we thought to be most important to the manufacturing process in order to discuss with them whether they agreed or not, or if they could think of any other criteria that should be presented in the matrix. Furthermore, we wanted them to weigh up the criteria according to their experience and expectations.

Firstly, these were the criteria we included in the matrix, defined upon the problem formulation made in the beginning, capturing the real objectives of the project:
• Model & casting design time: This criterion measures how quick the early design stage is done, from the original source -drawings/sketches or CAD-files- to the first physical model and moulds.

• Time to pattern: This criterion measures how quick the solution is being evaluated achieves the mother mould -ready for production- after the first stage.

• Materials cost: This one takes into account the amount of material used in the solution and its cost, involving complementary expenses such as coatings and/or post-processing.

• One-time model (for exhibitions): This criterion is more qualitative than quantitative, as what it defines is how a solution helps solve the problem of the unique models for presentations that will never be produced.

• Specialized knowledge on technique: This compares what the investment in know-how must be in every solution.

• Quality/quantity of the moulds: This evaluates how the different solutions perform when it comes to making the moulds for production -number, cost and quality of them-.

• Communication: This criterion measures how well each solution fixes the problems of communication between the development and the manufacturing areas.

• Salaries: This is what the cost of the labour is in every solution.

• CAD/CAM licenses: The cost of the software required to introduce the solutions in the chain process.

In our reunion with the people from the company we discussed the criteria and they decided that they were representative of the factors involved in the production process. Weighing the criteria took a long time, in which they discussed about the issue, and the final matrix, with our rates to the concepts, is as follows:
“Design of a CAD and Rapid Prototyping based production process for porcelain”

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Weight</th>
<th>A (reference)</th>
<th>B 3D-Printer(Plaster)</th>
<th>C 3D-Printer(elastomeric)</th>
<th>D Polyurethane casting</th>
<th>E CNC</th>
<th>D SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model &amp; casting design time</td>
<td>20%</td>
<td>3 0.60</td>
<td>5 1.00</td>
<td>5 1.00</td>
<td>3 0.60</td>
<td>5 1.00</td>
<td>5 1.00</td>
</tr>
<tr>
<td>Time to pattern</td>
<td>5%</td>
<td>3 0.15</td>
<td>2 0.10</td>
<td>5 0.25</td>
<td>3 0.15</td>
<td>5 0.25</td>
<td>3 0.15</td>
</tr>
<tr>
<td>Materials cost</td>
<td>2%</td>
<td>3 0.06</td>
<td>3 0.06</td>
<td>2 0.04</td>
<td>4 0.08</td>
<td>4 0.08</td>
<td>1 0.02</td>
</tr>
<tr>
<td>One-time model (for exhibitions)</td>
<td>40%</td>
<td>3 1.20</td>
<td>4 1.60</td>
<td>2 0.80</td>
<td>3 1.20</td>
<td>4 1.60</td>
<td>4 1.60</td>
</tr>
<tr>
<td>Specialized knowledge on technique</td>
<td>5%</td>
<td>3 0.15</td>
<td>2 0.10</td>
<td>2 0.10</td>
<td>3 0.15</td>
<td>1 0.05</td>
<td>2 0.10</td>
</tr>
<tr>
<td>Quality/Quantity of moulds</td>
<td>20%</td>
<td>3 0.60</td>
<td>1 0.20</td>
<td>1 0.20</td>
<td>3 0.60</td>
<td>3 0.60</td>
<td>3 0.60</td>
</tr>
<tr>
<td>Communication</td>
<td>8%</td>
<td>3 0.24</td>
<td>5 0.40</td>
<td>5 0.40</td>
<td>3 0.24</td>
<td>4 0.32</td>
<td>4 0.32</td>
</tr>
<tr>
<td>Total Score</td>
<td></td>
<td>3.00</td>
<td>3.46</td>
<td>2.79</td>
<td>3.02</td>
<td>3.90</td>
<td>3.79</td>
</tr>
<tr>
<td>Rank</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 55. Pugh’s matrix

Though CNC is the most rated solution, an analysis of the matrix is needed, as there are some other factors that are not represented in the chart that must be taken into account. For this, we can check all the criteria separately:

- **Model & casting design time** is not a crucial criterion, as the rating is the same for all the concepts, given that all of them are CAD based, the time spent in modelling being the same. The only one that does not have such a rating is solution 3, as the process is completely the same than the current one.

- **The time to pattern** is short for 3D-Printer used with elastomeric material and CNC, since a mother mould can directly be made out of the CAD data. However, CNC still has advantages over the others, with a larger working envelope and much higher accuracy.

- Polyurethane materials, both boards and RTV-resins are cheaper than RP materials. Nevertheless this criterion was given little weight by the company -only 2%-., so its influence is almost negligible.

- **One-time model** is considered the worthiest criteria in the matrix with 40 %. Despite 3D-printers build quickly models in plaster, surfaces require polishing and coating. Both CNC and SLA techniques make it expensive due to it is necessary to build moulds for casting the model. However it is cheaper and faster than the traditional way.
• Whichever technique, there is a need to invest in know-how, and this can be mostly time, money or both. Anyhow, this criterion was given so little weight because the company pretends to outsource the prototyping works, this depending on the difficulty of the technique. Even 3D-Printers require some learning to be used properly.

• The quantity of the moulds, or more precisely the ratio of quantity/quality of the moulds to price of them is a crucial point in the process. This criterion shows that the best the solutions can perform is as good as the current process. CNC, SLA and polyurethane casting provide the best moulds because of the accuracy of the mother moulds, as good as current silicone mother moulds, whereas 3D-Printers provide patterns nor accurate neither durable enough.

• 3D-Printers have, unlike in the previous criterion, the highest rating in communication. This is because these machines are the easiest to use, with very fast speeds when building visual models. With a 3D-Printer the interaction between designers and manufacturing can be considerably improved, just as in Denby's case, eliminating the traditional drawings and sketches from the process. Once again, a physical object is the best way to communicate, and 3D-Printers create models inexpensively.

• The other two criteria we had included in the matrix -salaries and CAD license- were discarded because the board of the company gave them a weight of 0%.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

FINAL SOLUTION

After the discussion with the company, which gave us a new and more profound perspective of the issue, we used the output of the matrix to develop a new solution that would join the strengths of the different concepts, enhancing the process significantly. The result is a new process that blends solutions 1 and 4, as the figure below shows.

Firstly, the modelling is done with CAD software. This modelling involves the object that is going to be produced and, depending on the complexity and communication factors, the design of the casting, with the moulds and their channels to pour the clay in. This is basically to help visualize the whole process from the very beginning. Furthermore, this parts can all be printed, to handle the physical models and discuss over them and test how the casting process might work. This serves as
a channel of communication between the product design developers and the manufacturing area, and also with directors in the company, or even customers and testers. If the moulds are too large for the ZPrinter machine, the parts can be scaled, as they serve only for testing purposes.

The main advantage in this stage is the flexibility when making changes in the modelling. If a virtual model is printed and finally not approved, it just takes minutes to move back to the 3D-modelling and make the appropriate changes. After this, the part can be printed again, thus having an iteration until the model is tested and approved. These changes in the CAD file are easy to carry out, unlike traditional modelling with plaster. Depending on the changes a plaster model may require, the process of hand-modelling must be started all over again, which does not happen with 3D-modelling.

Secondly, once the design has been approved, the shape of the product is milled out from a block of milling board to get either a negative -if a plaster positive is required- or a positive -mother mould-. The advantage of this entire process is that CNC works with the same digital input than RP machines, so that changes in the 3D-CAD files are not needed.

Subsequently, the moulds for production can be cast in the mother mould, leading to a quicker and more efficient production. The polyurethane milling material has very good dimensional stability and humidity resistance, being able to withstand hundreds of castings.

To ascertain that this solution is better than the solutions it comprises and the discarded ones, we assess it with the same matrix we have used for the others.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

As can be seen, the final solution gets a rating of 3.94, compared to 3 for the reference. Though it may seem that the gap between this solution and the early solutions -CNC, for instance, with 3,90- is not very big, there are some considerations that increase the value of the former.

Concerning the first and the second criterion, the final solution does not seem to improve anything with regard to the CNC solution. On the contrary, there is the advantage mentioned previously of having a physical model, that serves as a communication device and helps fix errors. In the CNC solution the mother mould can be achieved with much velocity, but this alternative skips the possibility of a physical model.

About a possible implementation and investment, the board of people with who we discussed acknowledged that there is no will in the company to invest in a big machine that would demand new skills within the personnel. The CNC milling step would be sourced out to any company, since the operations to mill a block of material should not take more than 1 or 2 days, and the prices are lowering everyday. Contrary to CNC, they would be willing to purchase a 3D-Printer because these machines are easily affordable and they do not require high skills beyond knowing how to use standard CAD software.

- 59 -
CONCLUSION

In summary, the process joins 3D-Printing and CNC milling in one solution that solves all the problems that were defined in the specification of the project.

The manufacturing process is greatly improved, with much shorter times to market thanks to a quicker design phase. While in the current process the first stage takes half the time and cost of the process, in this solution the time is shortened and the need for skilled personnel in traditional crafts is reduced. The same goes to mother moulding, now done via CNC milling, that saves the laborious and time consuming step of casting rubber inside the moulds and letting it cure for several days. This process cuts time, therefore reducing costs.

The communication becomes more fluid and honest, as models can easily be printed in the RP machines and sent to several departments in the company to get the approval. In the case of the manufacturing area, physical models can be sent with their corresponding CAD files, which are a source of exact information about the product. Errors and misunderstandings should decrease and drawings and sketches would be no longer necessary.

The presentations of new series should never be a problem any longer because of the need of a one-time model. 3D-CAD modelling and 3D-Printing solve this issue in a simple way, being able to produce functional prototypes, such as pouring teapots, with whichever shape that can be imagined. Some post-finishing work is required though -coating, sealing and polishing the part-.
BIBLIOGRAPHY

LITERATURE

“Design of a CAD and Rapid Prototyping based production process for porcelain”

Tooling”. Bachelor of Science in Mechanical Engineering, Cleveland State University.


16. INTERNET

17. ZCorp. 3D-Printing systems. 27th February 2008. <www.zcorp.com>

18. Porcelain: information on how it is made. 24th February 2008.  
   <http://www.madehow.com/Volume-1/Porcelain.html>


   <http://cebex.se/english/>

22. Crocker, B. “Plaster isn’t so hard to use”. 29th March 2008  
   <http://www.ceramicstoday.com/articles/plaster_a.htm>

   <http://www.engineershandbook.com/RapidPrototyping/>

   <http://findarticles.com/p/articles/mi_qa3957/is_200502/ai_n9521052>


   <http://www.autonomic.org.uk/>


   <http://www.portec.ch/seiten/ceramic.html>


40. 2Objet. 3D-Printing systems. 1st March 2008. <www.2objet.com>

41. 3DSystems. Rapid Prototyping machines. 3rd March 2008. <www.3dsystems.com>


43. ProtoCAM. RP services. 15th April <www.protocam.com>

44. Denby Pottery case study. 2nd April <http://www.zcorp.com/documents/121_CaseStudy-Denby-FINAL.pdf>


## APPENDIXES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix 1</td>
<td>Scanners</td>
<td>2</td>
</tr>
<tr>
<td>Appendix 2</td>
<td>Solution 1</td>
<td>3</td>
</tr>
<tr>
<td>Appendix 3</td>
<td>Solution 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendix 3-1. ElastosilDatasheet</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Appendix 3-2. MaterialsDatasheet</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Appendix 3-3. Renders</td>
<td>7</td>
</tr>
<tr>
<td>Appendix 4</td>
<td>Solution 3</td>
<td>8</td>
</tr>
<tr>
<td>Appendix 5</td>
<td>Solution 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendix 5-1. MaterialsDatasheet</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Appendix 5-2. Renders</td>
<td>10</td>
</tr>
<tr>
<td>Appendix 6</td>
<td>Solution 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendix 6. MaterialDatasheet</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Appendix 6. Renders</td>
<td>12</td>
</tr>
<tr>
<td>Appendix 7</td>
<td>Volume Calculations</td>
<td>13</td>
</tr>
<tr>
<td>Appendix 8</td>
<td>Glossary</td>
<td>14</td>
</tr>
<tr>
<td>Appendix 9</td>
<td>Software</td>
<td>18</td>
</tr>
<tr>
<td>Appendix 10</td>
<td>Brainstorming</td>
<td>24</td>
</tr>
<tr>
<td>Appendix 11</td>
<td>Contacts</td>
<td>25</td>
</tr>
</tbody>
</table>
APPENDIX 1

The technical data of the scanners can be found in the following links:

MicroScribe G2

http://microscribe.ghost3d.com/gt_microscan-3d_faqs.htm

Roland LPX-600


Scanner 700

Part.stl built with Pro-Engineer. This piece is ready to be manufactured via 3D printer since it is referred to .stl formal, which means that the piece is divide into layer/slices through it can be built with this RP technique.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

APPENDIX 3-1

ELASTOSIL® M 4643 A/B
RTV-2 Silicone Rubber / Mold Making

Characteristics
Pourable, addition-curing, two-component silicone rubber that vulcanizes at room temperature.

Special characteristics
• Very good flow
• Fast and non-shrink cure at room temperature which can be accelerated considerably by the application of heat
• Medium Shore A hardness (approx. 48)
• High tear strength
• Long-term stabilization of the vulcanizate’s mechanical properties
• Excellent resistance to the common casting resins

Application
Due to its outstanding resistance to casting resins as well as its superior mechanical properties ELASTOSIL® M 4643 A/B is perfectly suitable for all molds of models with undercuts that are to be reproduced in casting resins, and a certain inherent rigidity of the molds is required.

As a medium-Shore addition-curing RTV-2 silicone rubber that cures without undergoing dimensional shrinkage, ELASTOSIL® M 4643 A/B is also extremely suitable for casting all other common reproduction materials, particularly if absolutely accurate copies of models with undercuts are required.

Product data (uncured)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>White</td>
<td>Dark gray</td>
<td></td>
</tr>
<tr>
<td>Density at 23 °C</td>
<td>[g/cm³]</td>
<td>1.41</td>
<td>1.00</td>
</tr>
<tr>
<td>Viscosity at 23 °C, after stirring</td>
<td>ISO 3219</td>
<td>[mPa s]</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Product data (catalyzed A + B)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing ratio</td>
<td>A : B</td>
<td>9 : 1</td>
<td></td>
</tr>
<tr>
<td>Viscosity at 23 °C</td>
<td>ISO 3219</td>
<td>[mPa s]</td>
<td>25,000</td>
</tr>
<tr>
<td>Pot-life at 23 °C (up to 60,000 mPas)</td>
<td>[min]</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Curing time, tack-free</td>
<td>[h]</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Product data (cured)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Gray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density at 23 °C in water</td>
<td>ISO 2781</td>
<td>[g/cm³]</td>
<td>1.35</td>
</tr>
<tr>
<td>Hardness Shore A</td>
<td>ISO 868</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>ISO 37</td>
<td>[N/mm²]</td>
<td>5.0</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>ISO 37</td>
<td>[%]</td>
<td>300</td>
</tr>
<tr>
<td>Tear strength</td>
<td>ASTM D 624 B</td>
<td>[N/mm]</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Linear shrinkage</td>
<td>[%]</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>After 24 h at 23 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These figures are only intended as a guide and should not be used in preparing specifications.
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Processing

Important
The platinum catalyst is contained in component B.

Caution
Only components A and B that have the same lot number may be processed together.

Comprehensive instructions are given in our leaflet "Wacker RTV-2 Silicone Rubber - Processing."

Detailed information on other mold-making compounds in the ELASTOSIL® M range is contained in our brochure “ELASTOSIL® M, Mold-Making Compounds For Maximum Precision”.

Storage

ELASTOSIL® M 4643 A/B should be stored between 5 °C and 30 °C in the tightly originally sealed container. The ‘Best use before end’ date of each batch appears on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. In this case however, the properties required for the intended use must be checked for quality assurance reasons.

Safety Information

Components A and B of the addition-curing grade ELASTOSIL® M 4643 contain only constituents that over many years have proved to be neither toxic nor aggressive. Special handling precautions are therefore not required, i.e., only the general industrial hygiene regulations apply.

Detailed safety information is contained in each Material Safety Data Sheet, which can be obtained from our sales offices.

Additional Information

Please visit our website www.wacker.com

---

The data presented in this leaflet are in accordance with the present state of our knowledge, but do not absolve the user from carefully checking all supplies immediately on receipt. We reserve the right to alter product contents within the scope of technical progress or new developments. The recommendations made in this leaflet should be checked by preliminary trials because of conditions during processing over which we have no control, especially where other companies' raw materials are also being used. The recommendations do not absolve the user from the obligation of assuring the possibility of infringement of third parties' rights and, if necessary, clarifying the position. Recommendations for use do not constitute a warranty, either express or implied, of the fitness or suitability of the products for a particular purpose.

The management system has been certified according to DIN EN ISO 9001 and DIN EN ISO 14001.

WACKER and ELASTOSIL® are registered trademarks of Wacker Chemie AG.

Version 7.04 from 28-08-07 replaces Version 6.04 from 11-04-07

For technical, quality, or product safety questions, please contact:

Wacker Chemie AG
WACKER-SILI-CONS
Henne-Siedelplatz 4
D-81737 Munich, Germany

www.wacker.com
silicones@wacker.com
APPENDIX 3-2

Materials solution 2
All datasheet can be found in this links.

**Somos 9120**
www.stereolithography.com/

**Tango Plus, FullCure 930**
www.2objet.com

www.skaramodellsnickeri.se

**Duraform Flex plastic**
www.3dsystem.com
APPENDIX 3-3

The next figures show the .STL render parts referring to the solution 2. The grey part is has to be made of flexible material which joins with the plaster box in order to construct the mother mould for casting the moulds for production. The part also possess the gate of a mould to cast the clay when the mould is done.
APPENDIX 4

Material Datasheet:

RenCast series


Freeman 1040 elastomer


Pu 342 ab (Alchemie)

http://www.alchemie.com/mould_making.htm
APPENDIX 5-1

Technical brochure of RenShape 5460

APPENDIX 5-2

The renders corresponding to the solution 4. The mother mould is made in one polyurethane piece.

Figure 1. 3D-CAD file for polyurethane mother mould.

Figure 2, 3. 3D-CAD file for polyurethane moulds.

In the second option, polyurethane moulds, the point is that we can get the first plaster model just casting the plaster in these moulds.

APPENDIX 6-1
Material Technical Datasheet

SLA, 3D System

http://www.3dsystems.com/products/index.asp

DSM Somos

APPENDIX 6-2

Renders

Mould upper

Mould lower for casting the silicone and get the mother mould
APPENDIX 7

Volume calculation with Pro-Engineer tool

- Solid piece
  V = 5,25388 \times 10^5 \text{ mm}^3
  \text{Surface area} = 5,2715655 \times 10^4 \text{ mm}^2

- Silicone part in the mother mould
  The estimation is done for a 8 mm wall thickness
  V = 2,505718,58 \text{ cm}^3;
  D = 1,35 \text{ g/cm}^3;
  M = D \times V;
  M = 3382718,9 \text{ g} = \sim 3,4 \text{ Kg}

- Shell part with 8 mm thickness
  V = 2, 3061955 \times 10^5 \text{ cm}^3;
  \text{Surface area} = 9, 3399216 \times 10^5 \text{ mm}^2
GLOSSARY

The following is a list of common terms related to RP, ceramics manufacturing and 3D-Scanning:

CAD - Computer Aided Design. CAD is a standard term defining a group of software that aides in design. CAD software is what is used for 3D modelling and to create 2D drawings. It is typically used in manufacturing or other engineering disciplines. For example: An engineer designs in SolidWorks, Pro-E, AutoCAD, CATIA, or Unigraphics; all of which are CAD.

3D Modelling - 3D modelling refers to the creation of three-dimensional objects that are defined mathematically and geometrically (i.e. a circle extruded to a certain value to create a cylinder defined by its location, radius and length). 3D modelling can be aided by the use of scan data (see Reverse Engineering).

3D Scanner - 3D scanners come in many forms, but the purpose of every one of them is to capture the shape, and sometimes colour, of real-world physical objects or environments. This captured data is typically stored as a list of xyz-coordinates in a point cloud file. 3D scanners can be categorized as contact (CMM arms) or non-contact (white light, 3D laser scanners, or stereo-vision based). Some can even capture internal features. "3D scanner" is sometimes misspelled as "3D scanner".

Accuracy - The accuracy is the closeness of a measurement to the actual feature. The opposite of accuracy is uncertainty, which is an inverse perspective of the same value.

Scan - Measuring the part, capturing data, and transferring the measured points to the computer. It also refers to the computer file that is based on the physical part, i.e., xyz coordinates that represent physical measurements taken by the scanner.

Resolution - Refers to the minimum increment in dimensions that a system achieve. It's one of the main determining factors for finish, appearance and accuracy, but certainly not the only one.

Pattern - An object or part which possesses the mechanical geometry of a final object or part, but which may not possess the desired mechanical, thermal or other attributes of the final parts. Patterns
are used in secondary processes to form tools to make parts for end-uses. In the report, following the company's terminology, they are called mother moulds.

**Rapid manufacturing** - Refers to the process of fabricating parts directly for end-use from a rapid prototyping machine. A synonym is direct manufacturing.

**Rapid prototyping** - Computer-controlled additive fabrication. Commonly used synonyms for RP are: 3-Dimensional Printing, additive fabrication, freeform fabrication, solid freeform fabrication, stereolithography. Note that most of these synonyms are imprecise.

**Rapid tooling** - Most often refers to the process of fabricating tools from a rapid prototyping process. Rapid tooling may utilize direct or indirect methods: In direct methods, the part fabricated by the RP machine itself is used as the tool. In indirect methods, the part fabricated by the RP machine is used as a pattern in a secondary process. The resulting part from the secondary process is then used as the tool.

**Reverse engineering** - The process of measuring an existing part to create a geometric CAD data definition of the part. In common non-technical usage, reverse engineering may also refer to measuring or analyzing a part or a product for the purpose of copying it.

**Solid freeform fabrication (SFF)** - A synonym for rapid prototyping. The term is more precise and wider in scope, and somewhat favoured by the academic community. A variant is freeform fabrication (FFF).

**Subtractive fabrication** - Term used for all the fabrication technologies that, unlike RP additive techniques, eliminate material from a block.

**CNC machining** - Computer numerically controlled machining. It can be categorized as a subtractive fabrication technology. The input data for CNC machines is CAD/CAM files.

**Slipcasting** - Slip casting is a forming process used in ceramics, in which a powder suspension is poured into a plaster mould, which by its porosity creates capillary forces and removes liquid from the suspension (slip). Because of this, the powder particles are forced towards the mould walls and
a consolidated layer (filter cake) is gradually built up. When a desirable layer thickness has been obtained, the casting process is stopped. After a certain period of time the shaped piece can be released from the mould for further drying and firing (sintering).

**Pressure slipcasting** - Forming process that is similar to slipcasting, but instead of plaster moulds uses polymer moulds with an external pressure to increase the water absorption from the slip. It is much more efficient, but also costly.

**Bisque** – Unglazed, fired clay.

**Ceramic Change** – The point at which, during firing, the clay becomes ceramic.

**Coefficient of Thermal Expansion** – The measurement of the length change of ceramic materials under temperature change. Ceramics expand while heating and contract while cooling.

**Firing** – The act of maturing the clay by heating inside a kiln.

**Glaze** – The liquid covering that is applied to bisque or greenware, which produces a hard, glassy surface.

**Greenware** – Clay objects that have not yet been fired.

**Kiln** – A high temperature furnace or oven, which is used to fire ceramics.

**Maturity** – The point at which ceramics have had the correct amount of firing.

**Mould (US English, mold)** – A permanent form that is used to press clay into a shape in preparation for firing.

**Porosity** – A term for the amount of pores, or empty spaces, within a material. Porosity should not be confused with permeability.

**Sintering** – Heating clay to the point at which it will no longer break down when exposed to water.
Slip - Clay mixed with water with a mayonnaise consistency. Used in casting and decoration.

Slurry - A thick slip.

Porcelain - White stoneware, made from clay prepared from feldspar, china clay, flint and whiting.

Drying shrinkage - Contraction that occurs when parts cool down. All clays shrink as they dry. After a pot has been made, it is left to dry before firing; the water of plasticity evaporates from the surfaces of the vessel and the clay particles are gradually brought into contact with one another. The finer the clay, the greater will be the shrinkage on drying.

Glaze - Glazes are vitreous coatings consisting of a glass former (usually silica) with the addition of a glass modifier, or flux, to lower its melting point.

Most of these definitions have been taken from the following sources:


Glossary of ceramic terms. 30th May 2008.

<http://www.tulane.edu/~kidder/Anth%20461/ceramic%20terms.html>

3DScanCo. 3D Scanning terms. 30th May 2008.

<http://www.3dscanco.com/about/3d-scanning/glossary.cfm#r>
APPENDIX 9

SOFTWARE RECOMMENDATIONS

All the solutions given in the Project involve 3D software for creating new parts or managing and using data from scans, which can be used as a basis for making changes or adding new shapes.

The Company asked us for suggestions about what software to use and the prices of the licenses. We are looking for an easy, general and complete programme that allows building and modifying parts from data introduced via scanning. This would allow to scan and work with parts provided by other craftsmen; both final designs and frame-shapes to be develop in depth with the computer.

The main point to bear in mind is the compatibility of the scanners when transferring files to other programs. Scanned data has the form of a 3D polygonal mesh (stl file) and can be imported directly in CAD programs, such the ones we will mention shortly, and the object can be modelled again from the mesh. This is because you do not get surfaces from the scanning, and in order to work with them in CAD programs there must be reverse engineering software in between, like Geomagic Studio, Rapidform X or Rhino Reverse. This software converts the 3D mesh into 3D surfaces.

The next list shows different programs that are normally used in CAD/CAM applications:

3D Modeling/Animation/Rendering Software
- 3ds max
- Maya
- LightWave 3D
- Form Z
- Autodesk VIZ

CAD/CAM/Inspection Software
- SolidWorks

- Mastercam
- Pro/ENGINEER
- CADKEY
- AutoCAD
- Rhino 3D
- SolidThinking
- Delcam PowerSHAPE
- Photomodeler scanner
- Rapid form
Immersion Software

- MicroScribe Utility Software
- Software Development Kit (PC and Mac)

MicroScribe Utility Software supports:

- AutoCAD
- AutoCAD Mechanical
- CADKEY

Compatible Software

- Excel
- Inventor
- Mastercam
- Mechanical Desktop
- Notepad
- Pro/ENGINEER
- Softimage|XSI
- Studio Tools
- SURFCAM
- Word

The most commonly used design software packages in ceramics industry are Powershape, Deskartes and Rhinos.

- **PowerShape**: is a total modelling program which allows to integrate surface, solid and triangle modelling. It is also possible to capture renders, making it easier to understand the final shape in 3D. It includes textures, shadows and many options that create images to be integrated in an environment with the aid of the assembly tool. Although it is about 3D, drawings can also be created to have a general idea of the part's measures.

![Figure 1: Designer from Homer](image)

This software is used, for instance, at Homer Laughlin Company, one of the main porcelain manufacturers in the US. One of the main features of the program is the Mould Wizard that automates some of the things needed for creating the moulds. A model is drawn on the computer and then PowerSHAPE is used to create two mould halves, as this software has built-in features to
help generate complex parting lines and split the molds in half, as well as other things that have to be done for every mould.

This program was also used in the project FLEXIFORM (pag 27) to create the moulds for pressure casting. The company VJ Goodall milled the shapes of the moulds with the data that came from this software.

The license cost for the standard version of this software is around 15400 SEK. There is a freeware version of the program called PowerShape-e 7350 that allows the user to use all the features, but does not have compatibility with any other CAD/CAM program, not even with PowerShape's commercial version. Whenever a consumer wants to export a file or manufacture it, this has to be done with PS Exchange, with a price of around 400 € per transaction.

- **DeskArtes:** 3Data Expert is utilized for different functions of 3D CAD data for Rapid Prototyping, 3D printer and simulation in companies like Z Corporation. All the models can be efficiently modified, until achieving the desired surface, and getting colours and textures for making the model more realistic becomes an easy step. It can also convert 3D models into drawings and analyze errors and number of components. Here we have some features according to the software information extracted from Nest Technologies Inc., DeskArtes website: (http://www.nesttechnologies.com/nest2/3DE_2.htm)

Visual inspection and measuring

- Visual model inspection with textures and colours
- Clipping and viewing with grid lines
- Take 3D measures to estimate the size
- Point value, angle, distance, radius
- Calculate areas and volumes
- 2D Dimensions and drawings
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Verifying the model

- Verify both surface and triangle models
- Analyze errors and number of components
- Gaps, inverted normals, overlapping surfaces, intersecting shells etc.

Generate good STL

- Fix Models Automatically or manually
- Auto Repair for fully automatic fixing
- Help Text to aid the repair work
- Interactive Editing for triangle data
- Flip triangle normals
- Connect separate components
- Reshape triangles for simulation

Prepare for 3D Printing

- Split models for separate or lower build
- Add pins to connect the ready parts accurately
- Hollow models for faster build
- Add Drain Holes to remove non processed material
- Offset solid models form open surfaces

Positioning part for RP

- Define platforms according to the size of your RP system
- Move parts to correct platform area
- Output STL or ZPR files with correct topology and colors for 3D Printing
DeskArtes software is used, for instance, by Denby pottery (Pag 22) in the building of their prototypes, because as it is said above, this program works perfectly with Zcorp's 3D-Printing systems.

The license cost for Design Expert standard version is around 7200 SEK, with an amount of 1800 SEK for annual upgrading. There are plenty of extra tools and plug-ins that cost more money.

- **Rhinoceros**: is a very popular design program with a large variety of supported import and export interfaces that make it flexible and compatible.

  Rhino can create, edit, analyze, document, render, animate, and translate NURBS curves, surfaces, and solids with no limits on complexity, degree, or size. Rhino also supports polygon meshes and point clouds. It can directly outputs STL, the language of 3-D printers and rapid prototyping systems. Special features for rapid prototyping include: model analysis, model repair tools, and accurate STL mesh control.

  Another point to take into account is that it has 3D digitizing support with MicroScribe. It also has some enhancing plug-ins, Claytools being one of the most powerful, especially when working with artistic free form products. This plug-in enables designers to use their sense of touch to rapidly create organic shapes and add sculptural details, handcrafted modifications and complex blends. The system uses a virtual clay metaphor that removes the constraints of technical modelling, strengthening the feel of creative expression.

  Rhinos' standard license is 6000 SEK. This quantity may be increased by adding plug-ins. For instance, Claytools plug-in costs even more than the program itself, with a cost around
16500 SEK.

As long as the company has already had some contact with Rhino, we advise them to continue using this program. It has a great advantage, which is that incredibly photorealistic renders can be done, which helps improve the name of the brand when showing them. Furthermore, the basic license is not expensive, and this standard version is quite enough to manage the models the company is doing.

Information in this appendix partly comes from the following sources:
- Product Development Inc. Information on Roland LPX 600. 1st June 2008. 
  <http://www.productdevelopmentinc.com/lpx-600/>
- MCAD Online. Information on PowerShape-e. 1st June 2008. 
  <http://mcadonline.com/index.php?option=com_content&task=view&id=266&Itemid=73>
- PowerShape homepage. <www.powershape.com>
  <http://www.nesttechnologies.com/nest2/3DE_2.htm>
APPENDIX 10
COMpanies and contacts

The following is a list of companies and individuals that have been asked along the working process, participating with answers and quotes.

Rapid Prototyping Companies

WE DO – 3D-Printing ZCorporation
Västmannagatan 66
113 25 Stockholm
08-313 744
0706-559932
info@wedo.se
www.wedo.se

CAD CREATION AB – 3D-Printing ZCorporation
Storängsvägen 26A
184 32 Åkersberga
Tel: 08 519 712 30
Mob:0707-738739

LOOM A – 3D-Printing Zcorporation - 3D-Scanning
Excercisgatan 2
211 30 Malmö
040-630 70 77
www.loom.nu

PROTOTAL AB – 3D-Printing ZCorporation, SLS, SLA
Instrumentvägen 6
E-553 02 Jönköping
info@prototal.se
phone:+46(0)3638 72 00
fax:+46(0)3638 72 40
www.prototal.se

SKARAMODELSNICKERI – SLA & SLS prototypes
Smedstorpsgatan 18,
532 37 Skara
Telefon: 0511-166 08
Fax: 0511-165 11
E-post: info@modellprototyp.se
www.modellprototyp.se

SOLIDMAKARNA – Zcorporation machines supplier in Sweden
Slottsvägen 14
Jönköping
Tel 036-16 68 70
info@solidmakarna.se
www.solidmakarna.se

STOCKHOLMS INNOVATÖRSKRETS – 3D-Printing ZCorporation
Cenneth Lindkvist
Hammarby Allé 3
120 32 Stockholm
08-694 76 60
cenneth.lindkvist@stik.se
http://www.stik.se/kontakt/4-stik/14-cenneth-lindkvist.html

PLASTIC, DESIGN & SERVICE (PDS) – SLA & SLS
Tistelvägen 2
SE-531 71 VINNINGA
+ 46 510 54 50 90
+ 46 510 50 62 7
E-mail:
info@pds.se
www.pds.se

Polyurethane suppliers

ABIC-KEMI AB – Casting resins & milling boards (RenShape products)
Fjärilsgatan 3
Box 6131
600 06 Norrköping
Telefon: 011-14 90 30
Telefax: 011-14 92 37
e-post : info@abic.se

CNC Companies

JIMEC AB – CNC Milling of files
Plastgatan 12A
S-531 55 Lidköping
SWEDEN
Phone: +46 (0)510 239 06
Fax: +46 (0)510 239 96
Cellphone: +46 (0)705 72 39 06
E-mail: jan.blom@jimec.se

SUNCAB AB – CNC Milling of files
Skeppareg. 1-3
Box 863
531 18 LIDKÖPING
“Design of a CAD and Rapid Prototyping based production process for porcelain”

Växel: 0510 27260
FAX: 0510 66920

UNNARYDS MODELSNICKERI AB – CNC Milling prototypes for casting
Österlänggatan 14
310 83 Unnaryd
Tel. +46 371 622 60
Fax. +46 371 602 32
info@unnarydmodell.se

Scanners

Protech AB – 3D-Printing Dimension & CAD/CAM software & MicroScribe Scanning systems supplier
Girovägen 13,
175 62 Järfälla
08 - 594 708 00
info@protech.se

Contacts

- Tavs Jorgensen (Research fellow, Autonomatics Research Center, UK). Expert in ceramics design and development and digital technologies. Consultancy tasks for ceramic companies. Tavs.jorgensen@rca.ac.uk
- Johan Nystrom (Solidmakarna, Zcorp supplier). Johan.nystrom@solidmakarna.se
- Ola Lyckfeldt & Erik Adolfsson, Keraminstitutet (Göteborg). Experts in slipcasting and rapid prototyping, respectively. Ola.lyckfeldt@swerea.se; erik.adolfsson@swerea.se
- Graham Small (Manager of CERAM Research Center, UK). Coordinator of the project FLEXIFORM. Researcher and consultant. graham.small@ceram.com
- G.P. Tromans (RP Consortium Manager, Loughborough University). Rapid Prototyping Research center. g.p.tromans@lboro.ac.uk
“Design of a CAD and Rapid Prototyping based production process for porcelain”