THESIS ON MECHANICAL ENGINEERING E95

Development of Additive Manufacturing Based on Functional Requirements

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Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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MEHHANOTEHNIKA E95

Funktsionaalsete vajaduste põhine kihtlisandustootmise arendus

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TTÜ KIRJASTUS

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INTRODUCTION
Problem Statement

Technology selection is a very complex process with many conflicting criteria that need to be satisfied at the same time. Usually this means compromises and sacrifices to balance cost, time, quality, and design. To decide what the best compromises are the engineer needs a vast knowledge base covering all the existing manufacturing technologies and large amount of experience. The following chapters describe various approaches and step-by-step instructions to technology selection. In most cases, it fundamentally consists of choosing the material and determining the production volume. Often the choices limited further by decisions made by the constructor in the design phase and by the machines available to the company. Technology selection requires high level of know-how about manufacturing processes from the engineer, an up-to-date overview of the entire manufacturing process and the machines' workload. This very time consuming and large-scale process, demands extensive experience, and it is very easy to overlook things. A quicker, more comprehensive solution is needed.

In the field of additive manufacturing technology selection may seem at the same time both easier and harder than the corresponding process in more traditional manufacturing. It is easier because the various additive manufacturing technologies allow creation of products with very different geometry with just one machine and extra tooling is not needed to create cavities, holes or any other feature. This means that even though the machines and manufacturing methods are differ greatly from one another, they can almost always be used to create the same product. The downside of this is that the choice between technologies and the machines becomes even more sensitive to cost, time, quantity and quality.

What makes the technology selection particularly difficult is that additive manufacturing is a relatively new manufacturing process and the field has few guidelines, examples, and case studies to offer. Because the machines can be used in such a universal way, traditional approaches are not applicable, not efficient, and/or dated. The second problem is that the machines and especially the materials used are constantly being developed and approaches that can be used today may not be usable tomorrow.

One of the less explored areas of research into additive manufacturing is the comparison and overview of the various technologies and their capabilities. There is a clear need for a comprehensive overview that compares individual additive manufacturing technologies and machines in the following (but not limited to) categories: the mechanical properties of the finished prototype, the product's appearance and surface quality, the cost of the prototype, the time needed for manufacturing, choice of materials, what kind of preparatory work and post- processing is needed, the cost of the prototyping machine itself, physical limitations to the product's geometry, and difference in measurements between computer model and finished product. These criteria have been chosen because additive manufacturing is still fresh, and relatively new means of production. With many companies and machines entering the market, we need to ensure comparable properties of the finished products. The necessity of this overview comes from the difficulty of selecting the optimal technology and machine for a given product. The problem arises from the fact that there is information available about the individual machines and their capabilities but the comparison in usually only between the machines from the same company. This overview is also needed for enabling better navigation in the field of additive manufacturing machines and technologies.

The prototypes themselves are often fragile and tend to break, especially if they are made with binder jetting technology. The problem lies with the mechanical properties of the products and of the materials. The two must be considered separately because the base materials mechanical properties are usually not the same as those of the finished product. The reason is that the individual layers are combined using a binding agent with different mechanical properties than the base material or melted together and thus changing the structure of the base material. The other factors distinguishing product's and material's properties are the post-processing of the products and positioning during production. This thesis focuses on product's mechanical properties and how we could improve them without changing the materials used.

The main objective of this work is to improve the optimal technology selection by using functional requirements and improvement of mechanical properties of products manufactured with additive manufacturing technologies.

The objectives with more detailed description are:

1) to validate the use of functional requirements in estimation of product's manufacturability, find the optimal production technology and simplify and speed up those two processes.

2) to improve, simplify and speed up the technology selection process in the field of additive manufacturing while also reducing the level on know-how required of the customer with regard to the production technology and machine selection.

3) to improve the mechanical properties of products manufactured with additive manufacturing technologies and decrease the disparity in their measurements.

Activities

Method for using functional requirements:

1) Using functional requirements in description and modelling of a product, process and company. Describing the theoretical background and principals for creating the models. Providing step-by-step instructions for creation of the process model.
2) Extending the theoretical base for use of functional requirements in the additive manufacturing technology selection process.
3) Stating principles and guidelines for designing the experimental testing of the materials used in additive manufacturing and for improving mechanical properties.

Outcome of the research:

1) A model created of a production process by using functional requirements based on a real life example of a company's detailed process description with physical parameters. Use of the model for determining technological capabilities of the company and to help simplify the technology selection process.
2) Proposal of a company model that is based on the process model using functional requirements. Introducing various stakeholders to the model and adding entities connected with the relevant functions. Also creating the connections between the functions and stakeholders/entities.
3) Application of the functional requirements approach to the field of additive manufacturing and improve the technology selection process.
4) Creation of a software program that assists in determining the optimal manufacturing technology and machine selection in additive manufacturing without the need of extensive know-how from the user. The program to be used in a real life example to verify the concept.
5) Compilation of a comprehensive and comparative overview of technologies and machines used in additive manufacturing wherein costs, various properties of materials and machines, quality, resources needed and geometrical limitations are listed.
6) Comparison of the tensile strength, modulus of elasticity and elastic elongation for products manufactured with binder jetting machine (ZPrinter 310) and plastic powder bed fusion machine (Formiga P100) through experimental testing.

Hypothesis

Hypothesis 1 – by describing a product, a process or a company with functional requirements it is possible to create a comprehensive model that helps to determine the optimal production technology. The model also provides the preliminary assessment on necessary resources needed for manufacturing.

Hypothesis 2 – applying functional requirements to the technology selection process and to determining product's manufacturability in the field of additive manufacturing, we can simplify and speed up the process in a novel way.

Hypothesis 3 – products mechanical properties manufactured by additive manufacturing technologies depend on changing the product's orientation in the building area and altering its post-processing. By changing them we can improve the mechanical properties of products manufactured with AM machines. Combination of bleed compensation, axis calibration and analysis of product's cross-section uniqueness can be used to reduce the prototyping and reduce the disparity between products' measurements and the measurements given in the model.

ABBREVIATIONS AND SYMBOLS

Abbreviations

3DP	–	three dimensional printing
ABS	–	acrylonitrile butadiene styrene
ASCII	–	American Standard Code of Information Interchange
AM	–	additive manufacturing
AMT	–	additive manufacturing technology
ASTM	–	American Society for Testing and Materials
BJ	–	binder jetting
BJT	–	binder jetting technology
CAD	–	computer aided design
CAM	–	computer aided manufacturing
ETHZ	–	Swiss Federal Institute of Technology Zurich
FR	–	functional requirements
FDM	–	fused deposition modelling
IIS	–	Internet Information Services (Internet Information Server)
IPT	–	inkjet printing technology
ISO	–	International Organization for Standardization
IT	–	information technology
ME	–	material extrusion
MET	–	material extrusion technology
MS	–	Microsoft Software company
NC	–	numerical control
PBF	–	powder bed fusion
PBFT	–	powder bed fusion technology
RFID	–	radio-frequency identification
SLS	–	selective laser sintering
SME	–	small and medium-sized enterprises
SST	–	soluble support technology
STP	–	filename extension for STEP and STEP NC
STEP	–	standard for the exchange of product model data
STEP NC	–	neutral data standard for computer aided manufacturing software
STL	–	standard tessellation language (data standard in computer aided design software)
TUT	–	Tallinn University of Technology

Symbols

a_m	–	additive manufacturing machine's pre-heating and curing time
c_m	–	average cost of a layer
E	–	modulus of elasticity
ε_b	–	elongation at break
FC_m	–	final cost of the product
FS_m	–	final score of the additive manufacturing machine
FT_m	–	final manufacturing time of the product
b_1	–	width of narrow portion
b_2	–	width at the ends
h	–	thickness
hl_m	–	layer thickness
H_x	–	maximum x axis length of the product
H_y	–	maximum y axis length of the product
H_z	–	maximum z axis length of the product
k_{mj}	–	question answer value
l_1	–	length of narrow parallel-sided portions
l_2	–	distance between broad parallel-sided portions
l_3	–	overall length
lr_m	–	number of layers
M_m	–	additive manufacturing machine number one
M_mR_c	–	cost priority value of the machine
M_mR_q	–	quality priority value of the machine
M_mR_t	–	time priority value of the machine
r	–	radius
PO_z	–	product's orientation in the z axis
PM_m	–	sum of points for the additive manufacturing machine
σ_m	–	tensile strength
R_a	–	surface roughness
R_c	–	cost priority value from customer
R_q	–	quality priority value from customer
R_t	–	time priority value from customer
t_m	–	average production time per layer
V_{box}	–	volume of products boundary box
x_{max}	–	maximum coordinate in the x axis
x_{min}	–	minimum coordinate in the x axis
y_{max}	–	maximum coordinate in the y axis
y_{min}	–	minimum coordinate in the y axis
z_{max}	–	maximum coordinate in the z axis
z_{min}	–	minimum coordinate in the z axis

1 THEORETICAL BACKGROUND ON FUNCTIONAL REQUIREMENTS AND ADDITIVE MANUFACTURING

1.1 Functional requirements

Functional requirements (FR) are most commonly used in software engineering (Kim *et al*. 1991; Haumer *et al.* 1998; Roya *et al.* 2001; Wiegers *et al*. 2013) and are often the bases upon which the whole system/program is built. Functional requirements determine what the program must achieve (Jackson 1997). It does not dictate in any way how the function must be achieved only what is expected of the program. It leaves the engineer freedom of choice as to how the program is constructed, what programming language to use and how the user interface will look.

For the same reasons functional requirements are introduced to mechanical engineering and specifically to technology selection. By describing a product just as a set of functions we leave open all the possible manufacturing options that are capable of creating a product that will achieve the goals set for it. So the main area where FRs could be used is work in the design phase or even in the concept phase, before the manufacturing technology is determined.

Manufacturing technology selection is usually done after the blueprints or CAD model have already been completed. This means that in this stage the engineer responsible for technology selection has two main decisions to make: determining the material(s) to be used and the size of the production batch(es) (Swift *et al.* 2003). The selection is quite limited because many of possibilities have been excluded by design of the product. In many cases there is only one solution how to manufacture that product. But this can mean that the company is put in a tight spot where it needs to use sub-contracting or acquire new machinery. Describing the product with functional requirements enables us to take a step back and redefine how the product is designed, think about why it is designed the way it is and consider alternative solutions with the same function.

A simple example of functional requirements usage in mechanical engineering would be a water bottle. The main function of the bottle is to hold liquid. This function can be served in very different ways: we can use a plastic bottle, glass bottle, carton container, paper or plastic cup, aluminium can *etc*. All these solutions satisfy the main functional requirement. If we add sub-functions to the products description we arrive at a more specific solution. When we take into account that the product has to be re-sealable, it has to stay intact during transportation, must preserve the liquid for a period of time, *etc*., we get a totally different solutions. For each of these solutions various manufacturing options are viable and can be used according to the company's needs and existing machines.

One of the recent developments in the field of functional requirements is determining the function for programs through free-form text analysis. This enables automatic creation (Zhang *et al.* 2002) of a list of functions the program must achieve (Sagar *et al.* 2014). These and similar parsers can be used to analyze STEP and STEP NC file formats (Xiao *et al.* 2015*)* and thereby automatically create the list of functional requirements for the product and, as an extension to that, automatically create a company model. The main reasons for using these parsers is to simplify the communication between the customer and manufacturer and to reduce the workload and the know-how needed by customers.

1.2 Overview of the research in the field of additive manufacturing

Additive manufacturing (AM) emerged with recent years' advances in computing technology and computing power. The first numerical control (NC) machines entered the market in the 1960's but the real revolutionary development began in the 1987 with Chuck Hall (co-founder of 3D Systems) developing the first patented and commercially available stereolitography machine SLA-1 creating a new paradigm for design and manufacture of new products (Wohlers report 2014). The main difference from existing prototyping technologies was that the new approach was an additive manufacturing instead of the material removing prototyping that had been the norm to that point. To distinguish the conventional prototyping/manufacturing from additive ones a new term was taken into use: additive manufacturing. This is a more comprehensive term that includes all the rapid prototyping technologies but because of the development in the field, the function of the machines are no longer just limited to prototyping but they are also capable of small-batch manufacturing.

The first additive manufacturing machines used stereolithography (involving laser and photo-sensitive liquid) (Lino *et al.* 2008) and the same technology is in use to this day but many other additive manufacturing technologies have been developed after that and some of these are described in the following chapters in detail. This thesis focuses on three additive manufacturing technologies — binder jetting- (also known as three dimensional printing), powder bed fusion- (also known as selective laser sintering), and material extrusion technology (also known as fused deposition modeling). These technologies are chosen because they are available for case studies and testing in Tallinn University of Technology (TUT).

Additive manufacturing process can be broken down into six major steps:

1) A virtual model is constructed using 3D CAD program.
2) Conversion into STL format.
3) A software program crates a layered model of the product.
4) The layers are created one after another by the additive manufacturing machine as the previous layers are lowered (or elevated) with the rest of the building area.

5) The model and any supports are removed from the building area.
6) The model is cleaned and if necessary — post-processed.

The materials used for creating the prototypes have evolved from liquid to plaster based powders to plastics and finally to metals (Grimm 2004). Currently AM technologies that use plastics and metals are the most widely studied and developed. The main reason for this lies in AM – customers want not just prototypes but products they can utilize. Because a very high percentage of products manufactured by conventional methods are made from metal and/or plastic, the focus has remained on those two materials. There are also great efforts made to create very inert materials to be used as medical prosthesis (Kalita 2009; Chua *et al.* 2014). AM technologies have also been applied to manufacturing muscles and organs, where the materials are various kind of living cells (Tran *et al.* 2014).

1.2.1 Additive manufacturing technologies

This section describes the three AM technologies that are the focus of this dissertation: binder jetting, material extrusion and powder bed fusion that are described in this section.

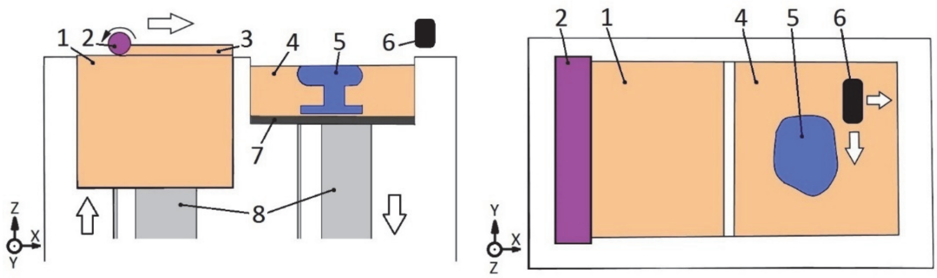


Figure 1.1 The general layout and working principal of binder jetting machine: 1– feed chamber; 2 – cylindrical sweeper; 3 – new layer of material being swept to building chamber; 4 – building chamber; 5 – prototype; 6 – printing head; 7 – removable base plate; 8 – cylinders moving feed- and building chamber.

Binder jetting technology (BJT) also known as three dimensional printing (3DP) and inkjet printing technology (IPT) – an additive manufacturing method where binding agent is added to a powder bed layer according to the cross-section of the product (Utelaa *et al.* 2008). Printing head (pos. 6 in Fig. 1.1) moves on the x-y axis to create the cross-section of the product and after the layer is created, building chamber (pos. 4) moves down one layer (on the z axis) and a new powder layer is created. The new layer of powder is usually created by counter rotating cylindrical sweeper (pos. 2) that moves along the x axis. The printing head creates the next layers of the product by adding binding agent according to the cross section until the product is completed. Cleaning and post-processing follow, these depend on the technology and the machine.

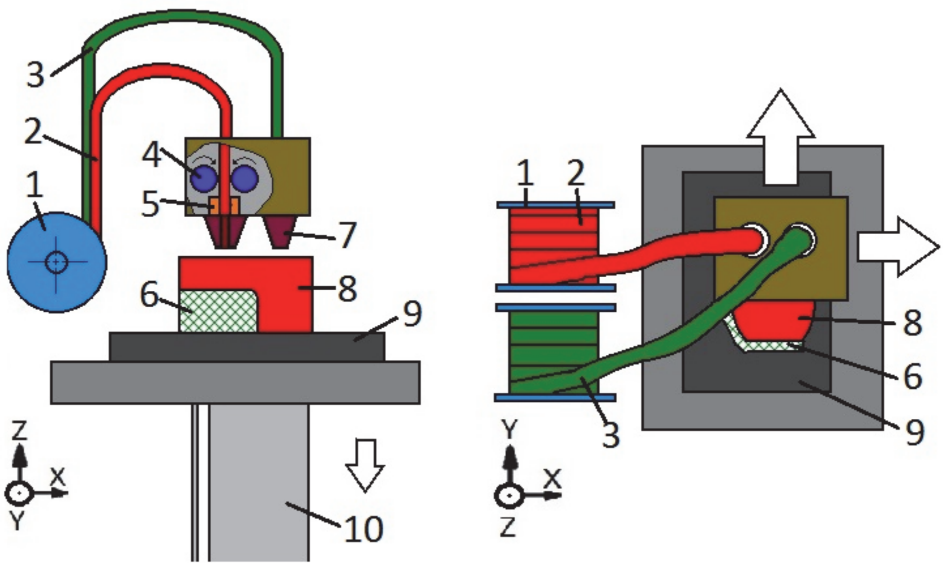


Figure 1.2 The general layout and working principal of material extrusion machine: 1 – build- and support materials' spools; 2 – build material filament; 3 – support material filament; 4 – drive wheels; 5 – liquifiers; 6 – prototype's support; 7 – extrusion nozzle; 8 – prototype; 9 – removable base plate; 10 – cylinder moving build chamber.

Material extrusion technology (MET) also referred as fused deposition modeling (FDM) and soluble support technology (SST) – additive manufacturing technology (Thrimurthulua *et al.* 2004) in which one (pos. 2 in Fig. 1.2) or more (pos. 3) filament (usually a plastic- or wax wire) is heated to the melting point and droplets of the melted material are deposited according to the cross-section of the prototype (see Fig. 1.2). Filament is fed from the materials' spools (pos. 1) to the liquefier (pos. 5) by driving wheels (pos. 4). The building area (pos. 9, 10) remains stationary during the creation of a layer as the nozzle (pos. 7) moves on x and y axis to create the layer. When a layer of the prototype is complete the building area moves down (on the z axis) by a layer and the AM machine creates the subsequent layers until the prototype is complete. If a product has extending features, a supports system (pos. 6) is created from another filament (pos. 3) to hold up these features. When the product is completed, the support system is removed either physically or by dissolving.

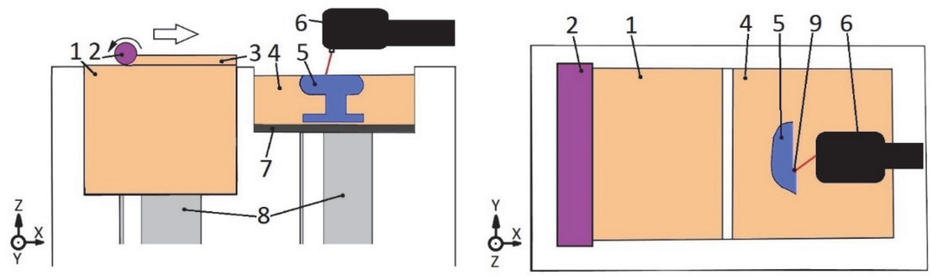


Figure 1.3 The general layout and working principal of powder bed fusion machine: 1 – feed chamber; 2 – cylindrical sweeper; 3 – new layer of material being swept to building chamber; 4 – building chamber; 5 – prototype; 6 – laser; 7 – removable base plate; 8 – cylinders moving feed- and building chamber; 9 – melting point.

Powder bed fusion (PBF) also known as selective laser sintering (SLS) – method where a high-powered laser (pos. 6 in Fig. 1.3), (usually CO_2 laser) sinters a cross-section of a product onto a powder bed (Goodridge *et al.* 2012). The laser beam moves on the x and y axis, building area (pos. 4) and feed chamber (pos. 1) in the z axis. The material used to create the bed is usually powdered plastic, but it can also be metal or ceramics. When a layer of the product has been created, the building area is lowered by a layers' thickness. Then a new layer (pos. 3) of fresh powder is swept across the building area. This continues until all the layers are completed and then the product cures in the machine for up to eight hours or 200 % of the building time. After that the excess powder is removed (and reused at least one time) and the product is cleaned.

1.2.2 Bleed compensation

All additive manufacturing technologies create the product by using a layered version of the product's CAD model. Each of the layers consists of data points. Every point has a binary value – "1" means that the point has to be sintered, plastic filament deposited on or binding agent jetted there depending on the type of the AM machine, "0" means that the point is to be skipped and no material/binding agent is deposited there. However with each technology the material deposited/sintered at any point not only affects the area designated for it but also will bleed into the area next to it. For example with BJT the binding agent will saturate the area around the printed point. This in turn means the precision of the final product will decrease. To counter the bleeding effect a bleeding compensation factor (also sometimes used as border offset) is included in the machines working parameters. If we continue with the BJT example, the higher the bleed compensation (depending on the machine) the smaller the binding agent droplet/amount of binding agent used. Smaller amount of binding agent/droplets reduces the area affected and help increase the precision of the product. In PBFT with high bleed compensation the laser beam will stay in the same position for shorter amount of time. The trade-off is reduction in structural integrity of the product so a compromise is necessary between these two properties.

Bleed compensation is with higher importance on products that have small features and/or complex geometrical shapes in their cross-sections. This is due to the increase in perimeter length on those products. The bleed effects are visually detectable only on the perimeter of a product's cross sections. If the cross-section is one simple geometrical shape, the bleed compensation effects can be reduced.

1.2.3 Axis calibration

Most AM machines have a standard configuration that featuring a printing/depositing head that moves in horizontal plain (with x and y axis motion) and a mechanism that lowers/rises the building area (on the z axis) by one layer. In most cases this is done by a threaded rod and a base plate which together acts as a bolt and a nut and is attached to the building chamber. As the threaded rod is turned, the building area will move up and down accordingly. Depending on the threading on the rod, one or more rotations may be needed to lower the building chamber by one layer.

One of the reasons axis calibration is needed for the x and y axis movement is that the printing/depositing head has enough weight that the inertia from the movement causes printing head to sometimes overshoot the coordinates given to it and that affects the precision of the product. Deviations caused by the peculiarities of the cross section are increased if the printing points are further apart. Another source of differences in measurements between CAD model and final product is the specific movement characteristics of the motors used to move the printing head. The third source is the minor changes of measurements takes place in the multiple translations involved (from CAD to STL, from STL to layered model). To compensate for these potential deviations a calibration coefficient is used on the machines. The axis calibration coefficient is represented as a percentage and all coordinates for that particular axis are multiplied with it. The coefficient depends on the peculiarities of the cross-section, model and AM machine used. It is important to note that thermal shrinkage (when the product cools and cures) also plays role when calibrating the axis but was not in the scope of this thesis.

The z axis (moving the building area vertically) doesn't have or need a calibration coefficient as the layers thickness is determined by the material used and the mechanical precision of the movement is usually not an issue. The newer models of AM machines provide the option of changing the layer thickness but it still remains a constant value and is not subject to an axis calibration coefficient.

1.3 Determination of the mechanical properties of products manufactured with additive manufacturing technologies

Developing new materials and improving the mechanical properties of existing materials used in additive manufacturing has become a rapidly developing field of research (Qian *et al.* 2007; Kumar *et al.* 2009; Tian *et al.* 2012; Guillotin *et al.* 2014). Testing the materials used in additive manufacturing is a complex task because different technologies and methods use very different materials — starting from liquid photopolymer and powder based materials and finishing with various metal alloys or even living cells (Kalita 2010; Chua *et al.* 2014). Testing all of these materials must be a similar and consistent process across all of the materials because the results must be comparable with the individual AM machines and technologies. The objective is to have comparable data points for evaluating AM methods and be able to compare future machines/materials tests with existing ones. The experiments conducted today are typically measuring the tensile- and yield strength and other mechanical properties but research has also been done to see how the different layers are bound together and how the different layers separate from each other and its' causes and mechanisms (Egodowatta *et al.* 2009).

Most of the materials that are already in use and being developed for AM technologies are plastics (or possess properties similar to those of plastics) and metals. The bases for creating a specimen for testing mechanical properties of products manufactured with AM can be found in existing ISO and ASTM standards (discussed in detail in Chapter 4) developed for testing plastics, aluminium alloys, and steel. Specimen based on these standards enable to determine the tensile - and yield strength, elastic elongation, modulus of elasticity and other mechanical properties of the prototypes. It is important to note that not the material in its pure form is tested, but the prototype itself. The difference is that in some cases a binding agent (BJ) is used to create the prototype or the material is melted and its' crystal structure changed (in PBF and ME). Additionally, some prototypes are also post-processed, meaning that they are covered with a resin. All of these reasons contribute to the changes is the mechanical properties of the final prototype compared to just the base material mechanical properties.

Another area of physical experiments is the measurement of surface roughness (Zhou *et al.* 2000; Campbell *et al.* 2002; Udroiu *et al.* 2009). Traditional measurement equipment is used because the prototypes do not have any additional limitation for surface roughness measurements when compared to surfaces manufactured with traditional production methods (Krolczyk *et al.* 2014). But surface roughness is usually evaluated only visually because most of the products manufactures are still just prototypes and used accordingly – as a visual representation of the final product and/or for ergonomical testing. The main evaluation of surface roughness is visual inspection and the surface quality is assessed on how profoundly different layers are noticeable on the surface.

2 DETERMINING OPTIMAL MANUFACTURING TECHNOLOGY ON THE BASIS OF FUNCTIONAL REQUIREMENTS

2.1 Use of functional requirements to determine the optimal manufacturing technology

Describing a product, process or a company with functional requirements is a relatively new and innovative approach in mechanical engineering. Creating models with FR hasn't been utilized that much because FR are mainly used in describing virtual products like software programs (McKay *et al.* 2001; Casamayor *et al.* 2010; Frece *et al.* 2012). Virtual or "meta" products are described with FR because the production methods (programming languages in IT) do not have so many limitations as physical ones. Most of the programming languages can be used to create the product, but some of the languages are better suited to carrying out certain assignments and the cost of creating that solution depends on the language used. The same situation occurs in the physical manufacturing industry: we have a choice between different suitable manufacturing technologies but some of the solutions are more efficient than others. The questions are how to find the optimal manufacturing technology and how much time is required for doing so. The product/company/manufacturing process is described with FR to simplify and speed up the process of finding the optimal production technology.

Because there was no prior model or description of a physical product described with FR in this specific form, reverse engineering has been used to create a product model. This starting point is to take a description of an existing product's manufacturing process. The description should be a step-by-step process in which each step it is described how and where the product moves and what physical transformations have been performed. Each of these steps was then analysed and transformed into functions. If all the steps have been described as functions then connections between the functions are found. The result we have a description of the manufacturing process as an FR model.

The next step is to add stakeholders to the model, entities responsible for or interested in the production of the product and its functions. Usually there are four stakeholders: the company, the customer, workers, and the product itself. This expansion of the model renders it more comprehensive and takes into account more factors of the product as a whole. Adding the stakeholders makes the model more structured and more suitable for real world use (for example it enables including the company policies in the model). If all of the stakeholders are added it is possible to choose one of them out and see all the FRs that are connected with it. With the product itself defined as a stakeholder so by identifying what are all the functions connected with it we have a FR model of that product and its' production process. This is simplified when using software shown in the example in Section 2.3.

If we have an FR model of a production process then the next step would be to compare that model to the machineries' FR model. Analyze has to be done on which kind of machines are or are not capable of fulfilling the FR that must be met in production of the relevant product. For that we have to describe the machines too in terms of functions. This is one of the biggest problems at the moment because to make that comparison we need a database of machines' function models and creating such a database is a difficult and time consuming process. However, because describing something with FRs is so universal, different types of machinery can be described by the same principles. We can describe a casting machine and a milling machine with the same parameters and that is the main advantage of using FR.

This comparison results in answers to two questions: firstly, is the product even manufacturable with the machinery it's compared to and secondly, if it is, what is the optimal manufacturing technology? For these answers we have to take into account also the physical/mechanical side of the product. For that non-functional requirements are used.

Non-functional requirements is a term used in IT (Chung *et al.* 2004; Chung *et al.* 2009) but in mechanical engineering these are also referred to as properties. These properties are added after the specification of the product has become clearer. Properties are there to make the usage of FRs more practical and connected with real manufacturing (Arubub *et al.* 2007). Categories of properties may include be (but are not limited to) physical, mechanical, visual or represent the quality of the product. Properties are not presented in the wording of the function, instead there is a special field dedicated to them, described in Section 4.1. Properties are kept separate from the function wording because otherwise it would create a function with excess and unnecessary information. One example of functional requirements with properties for our container case would be the following — function: "to have an opening for inserting liquid" and the properties field can specify "diameter of 30 mm".

These properties can later be used to help determine the optimal manufacturing technology because selection between methods is about not only the technical capability but also the physical limitations that have to be taken into consideration. Continuing with the example above, we can have a drilling machine that has a function to create an opening which would satisfy the "to have an opening for inserting liquids" function, but at the same time the drills that can be used in that machine are between 0,1 – 15 mm. This is specified in the machine's properties and eliminates that machine from consideration in technology selection for that company. If there is more than one machine capable of satisfying the functions the properties field can specify the cost per hour and the optimal machine/technology can be selected on that basis if cost is the most important factor.

Functions can also have sub-functions. The purpose of sub-functions is to clarify bigger functions and divide them into smaller ones. This is done to gain a better overview of all the resources and machines needed for manufacturing. The sub-functions are usually of the same nature and aim as the main function and have the same aim and ability to be achieved by the same machine. An example would be the following: the main function is “to cut the board into multiple pieces” and the sub-functions are “to cut the board lengthwise” and “to cut the board crosswise”.

In addition to determining the manufacturability and optimal production technology selection the FR model enables finding all the resources that are necessary to manufacture the product (Politze *et al.* 2010). For this we use the properties part of each function, where we can specify the resources needed. For example we can add a field to the properties in which the machine’s power consumption, labour costs, or tools required are described. This allows us to get a complete the list of resources needed for manufacturing.

2.2 Method based on functional requirements to determine the optimal production technology

Before FRs can be used in the production technology selection process, the first step is for an FR-based model to be created of an existing product’s manufacturing process. This model is used to determine whether FRs can even be used to model a manufacturing process. Reverse engineering was used for creation of the model, because there are no previous examples of FR usage in this specific way. Based on the model created, current technology used can be analyzed whether it is the optimal one and if necessary replaced with other manufacturing process.

The FR model of a product and its manufacturing process is also usable by companies that need to evaluate whether they are capable of producing a product. Large corporations and international companies do not have a complete and up-to-date overview of their production facilities. One of the reasons for this is that machines can be described very differently, a problem that using FRs solves.

The following steps should be observed for creation of an FR model:

1. Describe the manufacturing process – the product’s movement through the entire manufacturing chain
2. Divide the manufacturing process into elementary steps/operations
3. Determine functions for each step/operation and as necessary add sub-functions
4. Add properties to each step/operation as necessary

5. Add stakeholders
6. Find connections between functions and stakeholders
7. Determine the functions that are connected to the product
8. Analyze the products functions and find one or more suitable production technologies – use an automatic analyzer to compare the functions of the product to functions of the machines
9. Determine the optimal production technology on the basis of cost, time and quality criteria.

The subsequent paragraph is a more detailed description of each step with remarks on the possible pitfalls.

Step 1 – an existing manufacturing process description is analyzed and the product's movement through the entire manufacturing chain is specified. The description's comprehensiveness depends on the company. The manufacturing process can begin with a semi-finished product or even raw material and finishes when the product leaves the company or when it is recycled. If necessary the semi-finished products can be regarded as a separate model that can be used in the final model (it will consists of smaller sub-models). The production process description can be presented in any format but it has to cover all the operations that the product goes through. The description should also include all the physical dimensions that can later be use in the properties section of the function. This makes the model more realistic and connected to the real production.

Step 2 – the manufacturing process from step 1 is divided into elementary steps/operations. This means that every aspect of the production is described including transportation between machines, packaging *etc*. Each step can be divided into sub-steps when there is a need for clarification. The main step may be "cutting the workpiece to size" but because the operation is twofold: "cutting the workpiece on the x-axis" and "cutting it on the y-axis" sub-steps for those two operations should be used. Those sub-steps can also be used as the elementary steps but this can be a problem if the process description is very long. Whether to use sub-steps is a matter of preference and depends greatly on the specifics. The sub-steps give a clearer overview of the whole process and aids in to making a more informed decision. Additionally the sub-steps can be used to determine which tools are used for any specific operation on the same machine. For example drills of different size for different operations with the same machine.

Step 3 – one specifies what the functions of each step/process are. If sub-steps are used, sub-functions must also be used. The goal is to describe not how a machine or a person performs the process but what the purpose of the step is. This is one of the most important parts of creating the model because specifying the right functions is quite difficult and sometimes personal preferences in wording for the function can get in the way.

Step 4 – if necessary and possible, add properties to each function. This makes the function less abstract and also gives an overview of the machines involved in the production process and the operations needed for manufacturing the product.

Step 5 – add all the stakeholders connected with the product. In most cases there are four: the client, the company, workers, and the product itself. Stakeholders are participants in the process interested in different aspects of the product and those interest at some points overlap with each other. The stakeholders can be added or removed in accordance with the product. For example worker as stakeholder can be replaced with specific worker stakeholders for transportation, physical transformation and preparation.

Step 6 – connections between the functions have to be determined and each of the functions has to be connected to the stakeholders interested in or responsible for it. One function can be connected with many other functions and stakeholders. Connections are needed only between the main functions because each sub-function is already connected to its parent function. The connections do not indicate the sequence in which the functions/processes are executed but how they are dependent on each other. Once this step is completed, the FR model for a product's production process is complete.

Step 7 – Then, one defines all the main-functions and sub-functions that are connected to the product. This can be done manually but Section 2.4 provides an example of a software applications where this can be done automatically. If all the connections in step 6 are made this is a simple task of opening the product as a stakeholder in the program and seeing what functions are connected to it.

Step 8 – analysis of the functions that are connected to the product. This involves sorting out the functions that are directly connected to the manufacturing process. These functions determine which machines are capable of producing this product. For this we also need the functional description covering the machines themselves. Comparing these two lists of functions to each other gives us a list of machines that are capable of producing the product.

Step 9 – the list of machines created in step 8 needs to be ranked according to the optimal solution. Which solution is optimal is determined by three criteria: cost, time, and quality. These criteria have to be prioritized respectively to the optimization goals. In the properties part of the function for the product and for the machines, the average lead time, manufacturing time, costs connected with the workforce *etc*. are described. These properties allow to comparing the machines to each other and ranking them accordingly.

For further improvement of the model the machines workload, downtime and products planned for the future can be integrated into the properties part of the function. These parameters can be updated in real time, thereby making the model even more accurate. The inputs and outputs of each step are described in Fig. 2.1.

Figure 2.1 Inputs and outputs for each step for creating a FR model. The inputs are at the top of each step, the outputs at the bottom.

The main goal of the FR model is to determine the optimal production technology, and the secondary goal is to assess whether a given company is even capable of producing the product. This can be relevant when companies with diverse manufacturing capacity or a collection of smaller companies with different machinery have to decide whether they want to undertake the manufacturing of a new product. For that, step 8 has to be revisited and the match between the product and the machines no longer has to be optimal, the machines just have to be capable of producing the product.

A customer centered approach can also be used to create the FR model. This is useful if the company wants to start manufacturing a new product and the technology selection process is undetermined. When a customer centered approach is used to create the production model everything starts with the customer's needs and the company's desire to satisfy these needs. From the customer's needs we get what functions the product has to have. The company wants to satisfy those demands and has to design and produce a product that fulfills them. For that the company needs manufacturing capabilities. To add manufacturing to the model we firstly have to find the machines that are capable of producing a product with those required functions. If the machines are determined and the production process specified, then we get a list of required machinery, tools, workforce, *etc*. The model has to specify what make and model the machines are going to be, who the tool manufacturers are *etc*.

2.3 Model of a company and of a manufacturing process based on functional requirements

The theory and method described in Sections 2.1 and 2.2 clearly need a real life application to prove their validity. The following sub-sections show that this approach is viable and also has advantages over more traditional methods. The purpose of the model created on the basis of functional requirements is as following: firstly the company model shows that a company can be represented by means of FRs and that we can get a list of resources for whatever the company wants to manufacture and secondly that the manufacturing process also can be represented with FRs. The manufacturing process model can be expanded to a company model by adding stakeholders described in previous chapters.

2.3.1 Model of a company based on functional requirements

Creating the model starts with the customers' needs because todays' market is very customer centered (Randmaa *et al.* 2010) and mass customization is becoming more and more important for companies (Hart 1995), especially SMEs (Svensson *et al.* 2002). In Europe a very good example of satisfying the customers' needs through customization would be the Dorothy project (DOROTHY 2015), which focuses on fully customized shoe manufacturing and is part of the Manufuture (Manufuture-EU 2015) platform. Satisfying the customers' needs is the foundation on which the following model is built.

As already mentioned above, the FR model of a manufacturing process, a product or a company starts with the customer. The customer is the first stakeholder everything afterwards is derived from him or her. Fig. 2.2 shows an example of a company producing hammers. The potential customer has a requirement "to hammer a nail". That requirement creates a new FR "to buy a hammer". This is a very general functional requirement and needs to be specified with other FRs. For example should the handle be made out of plastic, and should it have certain measurements *etc*. These functions also have properties (non-functional requirements) through which we can specify and describe the type of plastic or length of the handle. The specifications are added once the manufacturing technology and production machines have been selected (see Table 2.1). But the FR "to buy a hammer" is the catalyst that starts the process wherein the company, manufacturing and the rest of the FRs come in.

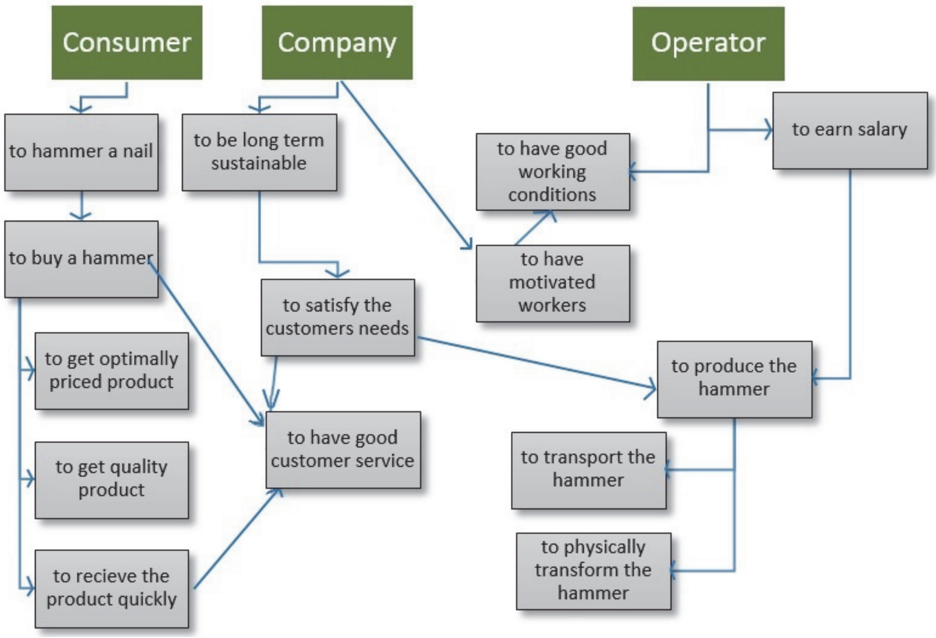


Figure 2.2 Example of an FR model based on the customer's needs.

The company's main objective is to be sustainable in the long run and to earn a profit as can be seen in Fig. 2.2. The company also wants to have loyal customers, increase its market share, have motivated workers and manufacture products cost efficiently but all these FRs are there to serve "to earn a profit" and "to be long term sustainable". And how does a company earn profit? By satisfying the needs of the customers, which in this example is "to buy a hammer". This is where the company's desire to manufacture hammers originally stems from.

The hammer also has to have some aesthetic and physical properties that are dictated by the customer. If it were possible, the company would produce the hammers at the lowest cost possible, with no standards of quality whatsoever. But the result would be a product that breaks when it is first used. If for some reason customers were willing to buy that sort of product, all the stakeholders involved would be satisfied (which is the main goal in business). But because customers always have requirements for quality the company must invest in equipment and technology to guarantee certain quality-related properties i.e., the functional requirement for quality actually comes from the customer not from the company. The company is, of course, interested in a quality product but only because it satisfies the customers' needs. For these reasons, the additional functions and properties are added to the model.

An example of properties is shown in Table 2.1.

Table 2.1 Properties and their values added to a function.

No.	Property name	Value	Operator	Tolerance	Unit
1	Squareness of elements	-	<=	+/– 0,03	mm/mm
2	Straightness of the surface layer	1400	<	+/– 0,05	mm/m
3	Height difference between elements	-	<	+/– 0,03	mm
4	Room temperature change	21	<=	+/– 3	°C

The next step is to add the workers, or "operator" to the model as a stakeholder. This is done because the product needs to be physically produced. The operator represents the workforce in general but can be specified as "transportation", "milling machine operator" or "packaging" in accordance with needs and the complexity of the model. Operators' and companies' basic FRs are very similar: both want to earn a profit/salary. As is shown in Fig. 2.2 the operator also has the FR "to have good working conditions" which reflects the motivation related part of the workers functional requirements. The following can be considered the motivation: long vacation, interesting and non-monotonous work and good working hours. These elements add to the complexity, comprehensiveness and usability of the model. It is important to remember that the motivational functions should be sub-functions (secondary) to the "earn salary" function because people are willing to work without a long vacation time but nobody is willing to work without a salary.

Now that we have all the stakeholders needed for the example, the next step would be to add the connections between the functions and stakeholders. By selecting a function we can see who the parties involved are and what their interests are in it.

2.3.2 Functional requirements as a process and company modelling tool

For the model we created software developed at the Swiss Federal Institute of Technology in Zurich (ETHZ) by the Inspire workgroup was used.

The model consists of three main parts as shown in Fig. 2.3: the left-hand column, the middle, where the relationship between functions are shown and the right-hand column. The column titled *Entity List* is on the left side of the model and consists of three main partitions. In the top partition in titled *Functions* and all functions that are part of the model are listed in alphabetical order. These functions can be part of the current model and in use in the middle part of the model or they can be stored there for future use. In addition to storing the functions, this partition also simplifies finding the functions. The latter issue arises when the model gets really big and complex what they sometimes tend to do and finding the right function can be tedious.

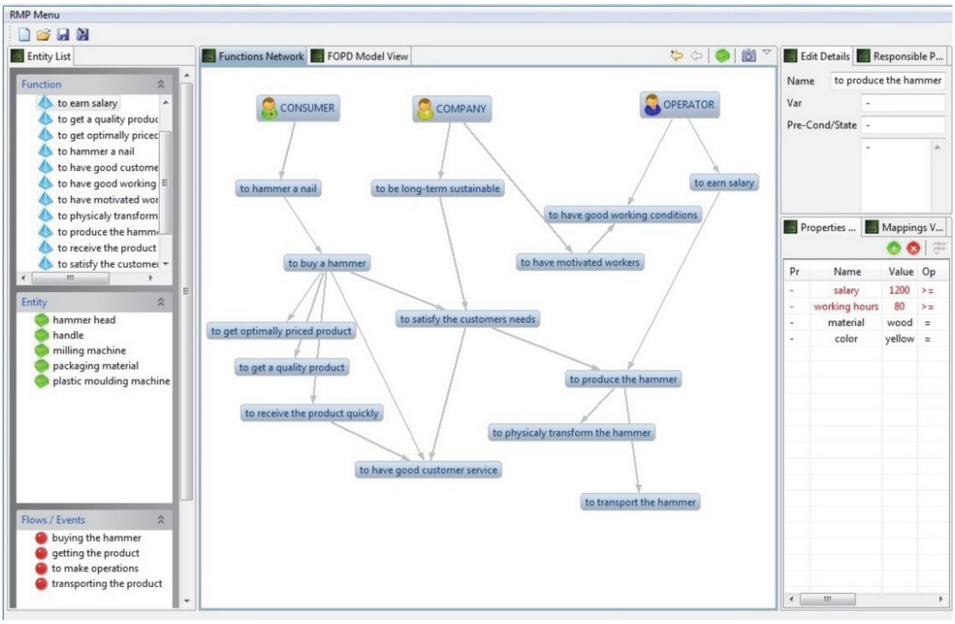


Figure 2.3 A simplified model of a company for manufacturing hammers on the basis of functional requirements.

The middle partition *Entity* holds all of the machines, materials, tools *etc*. that are required for the production process or for the company. These entities can be connected to functions. For example the entity “packaging material” can be connected to the “to transport the hammer” function.

The bottom partition titled *Flows/Events* enables describing various scenarios that can occur in the production process or what can happen to the company. By creating an event or a flow we can assign functions and entities to it and thereby examine and analyze what is happening in more specific parts of the model. For example, we can create a separate event for packaging and examine who the stakeholders are and what functions and entities are involved.

The biggest part, the central one, is the model itself. The column is titled *Functions Network* and this is where the model is built. On the first level are the stakeholders that have functions connected to them. As mentioned before the levels here do not represent the sequence in which the model should be constructed. That sequence was described at the beginning of this chapter. The arrows between stakeholders and functions show only those who are interested in the function in question, not the continuity. Because the models are sometimes reverse engineered, people tend to use the arrows as a way to show which process follow each other. The functions shown in Fig. 2.3 are arranged for better comprehension of the model not by importance.

In the top partition in the right-hand column, the details and further information about the functions are shown. This is where notes, comments and people responsible for the function are described. Also information about pre-conditions and prerequisite states is given if necessary.

The bottom partition of the right-hand column is designated for properties. This is the place where the physical parameters (non-functional requirements) are added, to make the whole model more tangible and connected to the production process (or the structure of the company). Each function and entity can have an infinite number of properties; their choice depends on what exactly is expected from the model and on its purpose. Time and cost are the parameters most common to be measured in that partition but surface quality, length-width and other dimensions, tools, raw material, energy consumption, goods to be purchased can be specified there. The only pre-condition for adding a property is that it has to be expressed with a measurable number or have a value from a list. For example a company producing soft drinks has different tastes for the beverages: apple, cola, strawberry, lemon *etc*. and these can be presented in the properties section for the appropriate function and be selectable from a list.

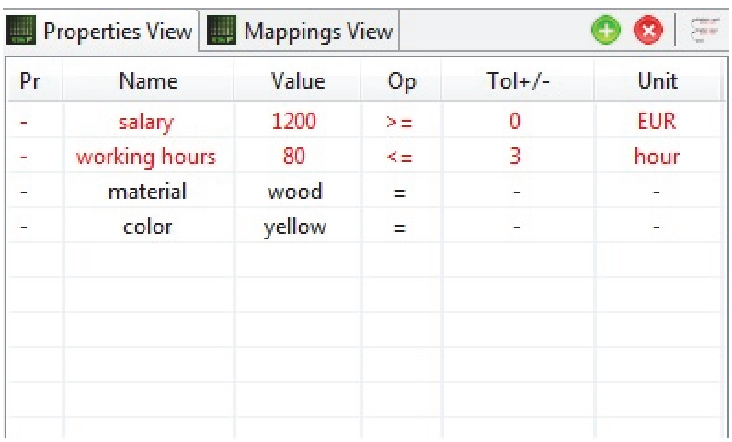
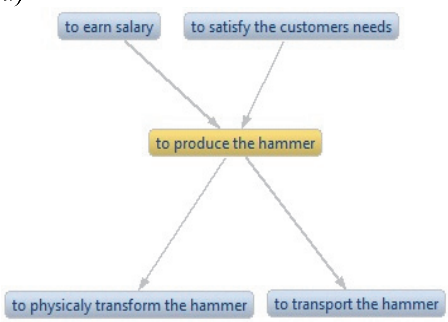


Figure 2.4 Example of properties (non-functional requirements) for a function.

Additionally the properties added could have both a required and desired value associated with them. As shown in Fig. 2.4 the *Op* column allows to define if the properties' values have to be equal to a certain value or instead are of a more advisory nature. The latter can be also that there is certain level that is required for the property, with values above or below that limit being desirable or at least allowed. The properties also have tolerances, with which the level of acceptable deviation can be defined. The value and tolerance must be expressed with the same unit of measurement. Units can be chosen freely and according to needs.

An example is given in Fig. 2.4 where the example function's "to produce a hammer" properties are specified. When any function in the model is selected, we see all the properties that are connected with it. The properties shown in red in Fig. 2.4 are inherited from previous functions in this case they come from the operator, whose properties are salary and working hours. The properties in black come from the functions below. In this example these are the properties of the handle, in which the where color and materials are indicated. To keep the example simple and understandable some of the properties are not shown here. The hammer head, packaging, transport, manufacturing *etc*. - all have their own properties.

a)



b)

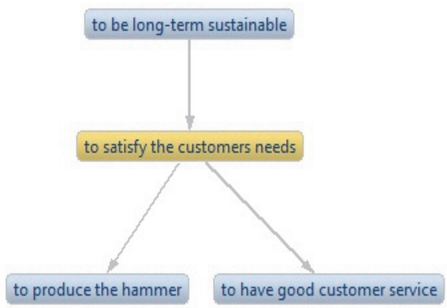


Figure 2.5 A user can inspect functions individually by selecting them from the model. The figure shows part a) functions connected to "to produce a hammer" and part b) connections one level upward.

To make the model more understandable and bring out the connections between functions Fig. 2.5 is presented, to show what happens when a function is double clicked in the program. The left pane (part a) shows the functions that are connected to the "to produce the hammer" function. The uppermost two functions show which functions or stakeholders are interested in it and below we see which functions it affects. In part b we see what happens when the function on the top right in pane a ("to satisfy the customers' needs") is clicked. We go one "level" upward and see what other functions are connected to "to satisfy the customers' needs". If we were to click "to be long-term sustainable" we would see what other functions and sub-functions would be connected to the company.

One of the goals of the model is to analyze the company's ability to produce a product and to improve on the optimal manufacturing technology selection process and to automate or semi-automate the process. This can be done once the functional model of the company and production process has been completed. The selection of the machines/technology is done by comparing the functions required of the product with the functions of the machine. For example if a product needs a hole in it with a certain diameter or has a freeform surface we compare all the company's machines to that functional requirement to see which of them have the function "to create a hole" and/or "to create a freeform surface" in their description. This is solved as a discrete mathematical problem with the answer being 0 or 1, with 1 being the positive result. If we get "1" as answers to all the production related functional requirements the company is capable of producing the product. We then take all the machines capable of satisfying the given function and compare them to each other. The basis for that comparison is for example cost, time or productivity as described in the properties section as shown (Table 2.1) above. From that comparison we determine which of the machines would be the optimal solution for the product.

Adding the entities to the model comes later when the machines' types have been chosen and confirmed.

The automation or semi-automation of technology selection and determination of a company's ability to produce a product can be carried out by using STEP or STEP-NC file types. These files are readable by humans and contain the geometry and information about production. In the example of having a hole or needing a freeform surface, these two features can be automatically detected from the file (similar to the way max-min coordinates are determined in Section 3.3). With each of these features an list of suitable machines/technologies can be automatically generated. Additionally, the header in STEP-NC contains extra information about the company *etc*. what can be used to create functions for the model automatically. For example the area of manufacturing can be specified — woodworking, sheet metal, electronics *etc*.

2.4 Summary of the chapter

In the discussion above it is shown that this approach is viable and it is indicated how a company or a production process can be modeled with FRs. The model itself, the peculiarities of the software used to construct it and the sequence in which the model should be built are described also. In addition to the example given in this chapter a case study was done where an actual production process was given by a company and by using reverse engineering it was converted to a model based on FRs. The goal for the case study was to investigate and determine the manufacturability of a product by that company, the production capacity, what resources were needed for production and the various options for rearranging the production line. The goal in creation of the model was to confirm the concept of using FRs for modelling a company/product/process.

The result of the investigation into the model created with reverse engineering proved that a model based on FR can be used to determine manufacturability and optimal manufacturing technology of a product from that company. This means comparing the functional requirements of the product to the functions of the company's manufacturing machinery. It is possible to obtain the information about the resources required (labour, time, costs, machinery) to manufacture that product. The level of detail of these resources depends on the level of detail in the model. If energy consumption is described in the properties part of the function it also is one of the resources required. The advantage to this approach is the reduced time to create comprehensive models of a whole process, company or product to determine manufacturability and optimal manufacturing technology along with identifying the resources required for manufacturing.

One of the advantages of using FRs is the universal way in which they can be used. This approach can be applied to companies with very different structures and operating in very different fields of manufacturing where they operate in. Even though the machines, the people and the roles they play in a company change, the function for all of them remains the same and this is why functional requirements can be used almost anywhere. In addition to creating the models of the company FRs can be used to model the process inside the company. Every step in the production process has its purpose, which can be translated into the function it must achieve. Therefore this approach can be applied to creating models of any process. To make the model more connected with actual production properties can be added to the functions where physical specifications can be given (for example the length and width of a product).

The main drawback to modelling with FRs at the moment is the lack of databases. There are very few models of production machinery or products themselves described in terms of with FRs. Building the model for the first time is time consuming and complicated for both the machinery and product. But if the first models are built for most widely used machines and certain type of products then the models of similar machines/products can be done quite easily –through adding of new functions and sub-functions or by removing them.

The second drawback involves identifying the correct functions. Although the functions have properties that connects them to the physical realm defining the functions can be somewhat subjective. This adds the difficulty of presenting the functions in an objective manner without needlessly limiting the realization of a function.

3 SELECTION OF OPTIMAL MANUFACTURING TECHNOLOGY IN ADDITIVE MANUFACTURING

3.1 Use of functional requirements to determine the optimal manufacturing technology in additive manufacturing

In Section 2.1 the theory for creating a model based on functional requirements of a manufacturing process was described. One of the main advantages of using FR as a modeling tool is improvement of the manufacturing technology selection process. This is done by comparing the FR of the product to the technological and functional capabilities of the machines available. For more practical output of the research, the focus is now turned to additive manufacturing and how FR can be used to improve the technology selection process in that field specifically.

AM technologies have been chosen as an example to be used in FR modeling because the machines are capable of producing products with very different functions, geometry and purposes. This enables exploring highly divergent options in FR modelling and aids in determining the best approach(es) for creating the technology selection model. Almost all the machines are always capable of producing the required product (very similar to programming languages) so the technology selection process is somewhat simplified. On the other hand however, we still need to identify the best technology/machine for any particular product. For this FRs will be used in a method described in Section 3.2.

There are three main criteria that are compared to determine the optimal manufacturing technology for a product: cost, time and quality. Each of these criteria have different relative importance depending on the product. For the comparison weights are used for each of the criteria, determined by the engineer or the customer. By changing the weights we get different manufacturing scenarios from among which the most optimal one can be chosen.

Cost – criteria measured in monetary value where the costs of materials, labour, machine exploitation and company overhead are taken into account.

Time – criteria measured in units of time, where preparing the CAD model for the AM machine, manufacturing (warming the machine, manufacturing, product curing in the machine) and post-processing are taken into account.

Quality – a somewhat ambiguous criteria that has different interpretations depending on the product. In most cases it means the product’s surface quality. Quality is a measurable property, measured with roughness parameter R_a but in most cases it is a visual evaluation of the products appearance. Visual evaluation is more widely used because most AM machines still produce prototypes not products and for prototypes the looks is more important than the actual surface roughness. Another dimension to quality is the products usability, often measured in tensile strength. It determines where and how the product can be used. The two quality criteria can have a required level or a desirable level depending on product's function. The required level stated for any quality criteria defines which additive manufacturing technology (AMT) is used and desirable criteria affect/determine which specific machine is used.

One of the reasons why AM technologies were chosen is the uniformity in how the communication between user, computer and machine is done. The same CAD model file can be used for all of the machines, thereby serving as a homogeneous input for the technology selection process.

Another reason for using AM is the trends and developments in machines, machining and production in general – additive production methods are becoming increasingly a viable option for manufacturing. This is especially in companies that focus on small production batches (up to 150 units) and mass customization.

Three different machines are used for creating the FR model and determining which of the machines is the best solution for creating any one product. These machines are: Z Printer 310 by ZCorp represents the binder jetting technology, ME is represented by 3D Touch by 3DSystems and the Formiga P 100 by EOS represents PBF. These machines represent the three AM technologies described in Subsection 1.2.1 and were used in this dissertation in the experimental part to verify various methods.

These machines were chosen because the manufacturing method for each machine is different and thus we get a more comprehensive technology selection model. Also the materials used by the machines vary: plaster based powder, PA220 (nylon), and ABS plastic. This too adds to the comprehensiveness of the model. One of the methods of verifying the results of the technology selection process is comparing it to past practices and because all of the machines are already in use in TUT, we can use the database of products already produced with these machines. An important reason for choosing these machines was, of course, their availability throughout the research and the opportunity to create specimens for identifying the resulting product's mechanical properties.

The existing solutions for determining the optimal AMT are limited to just a quote for price and time. The companies providing this service can be divided into two groups: companies that offer an online solution (RedEyeOnDemand 2015; Quickparts 2015; Oomipood 2015) and companies that offer a downloadable software program (Ultimaker 2015). With the first group the customer uploads a file (only in STL format), then chooses a technology/machine from the list, and in some cases specifies the material and the color. The biggest drawback is that to choose the right technology the customers have to have an engineering background or they must conduct considerable research to gain familiarity with various AM technologies. With the second group's (downloadable software) solution is developed for very specific machines, this is good only if one has those exact machines available for use.

The plus side with these software programs is the option to visualize the product and to position the products in the building area in the case of a bigger batch. In conclusion: the most considerable advantage of the FR approach is to make the technology selection without the engineering know-how, rest of the programming (quoting for price and time in the proposed solution) is relatively similar to the existing solutions.

AM technologies provide an example of how an FR approach can be applied and how in the future this research can be expanded to different production technology selection processes in many other fields of manufacturing. Furthermore, the next stages of research would entail also include other AM technologies to the same model and gradually increasing the model's complexity.

3.2 Method for using functional requirements to determine the optimal production technology in additive manufacturing

Production technology selection in AM is still in its infancy because it is a relatively new paradigm when compared to the traditional manufacturing methods. The main drawback in technology selection is that in most cases alternative production technologies are not even considered. Most companies that offer products manufactured with AM machines or providing a service for customers who supply their own CAD models, are using only one AM machine so technology selection is not a necessary step. But as the field develops and companies are starting to offer products manufactured with several AM machines from a single location, the need for the optimal technology selection becomes relevant because the cost, quality and manufacturing time vary up 10 times for different machines.

To find the optimal technology an approach based on FRs is proposed. AM as a manufacturing technology is selected to show that determining the optimal manufacturing technology from an FR based model of the product is feasible. The reason for choosing AM is twofold: the machines are capable of producing almost any product with very different functions (limited only by the base-material) and the availability of the machines for testing the results in TUT. Because all the machines are capable of creating free-form surfaces and any geometric shape the difference in the final products lie in the way they are created and how are they going to be used (in other words their functionality).

The foundation for technology selection begins with determining whether the machine is capable of producing a product that can fulfill the FRs lined to the product. If the machine is capable then what kind of cost, in how much time it has and what quality it can achieve. The combination of these three variables determine the optimal manufacturing technology. If there are multiple machines suitable for the manufacturing then the preference of the customer determines which machine to choose.

The solutions available at present for technology selection are for just one very specific machine and are more focused on the calculation of self-cost and the time required for manufacturing. Often these solutions are just MS Excel tables where the volume is inserted manually (attained from CAD model properties) and the time required for manufacturing (attained from the simulation run by the software that comes with the machine). The evaluation whether the product manufactured with a certain machine is able to fulfill the required functions is still a decision that requires engineer's knowhow. The method proposed here and the description of the software in Section 3.2 are for determining the optimal technology, to speed up the process and to limit or even eliminate the required knowhow needed for choosing the optimal AMT.

The method described below is meant for an online environment where any customer can upload their CAD file and get an estimate of the product's price, the estimated manufacturing time and which AM technology/machine to use without the help of an engineer.

Method for determining optimal AM technology/machine:

1. Determining the functionality of the product via questions to the customer.
2. Uploading a model to the online environment.
3. Prioritizing cost, time and quality.
4. Simulation and decision – presenting different scenarios.

The following discussion is a more precise description of each of the steps plus inputs and outputs shown in Fig. 3.1 below.

Step 1 – the most difficult part of the whole process is determining the functionality of the product. As mentioned above, when this approach is applied to AM which means the FR vary greatly since the machines are capable of manufacturing any geometric shape. To find out the functions, a free-form text parser (Sagar *et al.* 2014), described in Section 1.1 can be used but the customers rarely have that kind of text. Therefore in the approach proposed in this thesis a questionnaire is created to help figure out the functions of the product and thereby ascertaining the optimal AM machine/technology. The questions are in simple yes/no format or if necessary, a list of options to choose from. Creating a questionnaire with right questions is the greatest challenge because it needs to be universal and specific at the same time. Some examples of the questions have been given in Section 3.3. The answers to these questions limit and specify what kind of machines/technology can be used to manufacture the product (in functional terms).

Step 2 – on online environment needs to be created in order for the customer to upload the CAD model. This is the step e most of the companies offering AM services start with (RedEyeOnDemand 2015; Quickparts 2015; Oomipood 2015). Using the STL standard in CAD models is the most widely used format because almost all AM machines are using it for creating layered version of the product. The STEP and STEP NC formats are also viable options since they are universal and most of the CAD programs recognize them. The uploaded file is analysed, volume and maximum measurements in x, y and z axis defined and results compared to machines' building area size to eliminate machines with too small building area. The measurements also determine the cost and time needed for manufacturing the product.

Step 3 – the customer can determine which of the following parameter is the most important: cost, time or quality. These parameter can be represented as discretely defined list with one paramount condition and the others following it or weights can be added to the parameters. An example for the first case: if the time is the paramount condition then the machine with the shortest manufacturing time is the optimal solution. Example for the second case: quality might be the most important parameter but if the cost exceeds a certain limit, the solution is not acceptable.

Step 4 – the answers to the questions, uploaded CAD model's measurements and the prioritization of the cost, time and quality are all analyzed and various solutions are presented to the customer. The machines that fail in some key aspect of the product (functionality, measurements, tensile strength *etc.*) are eliminated and not presented in the results. All other machines are presented as viable options and the customer can decide which of them is most suitable. The order in which the results appear (i.e. which machine is deemed optimal) is determined in step 3 where parameters are prioritized.

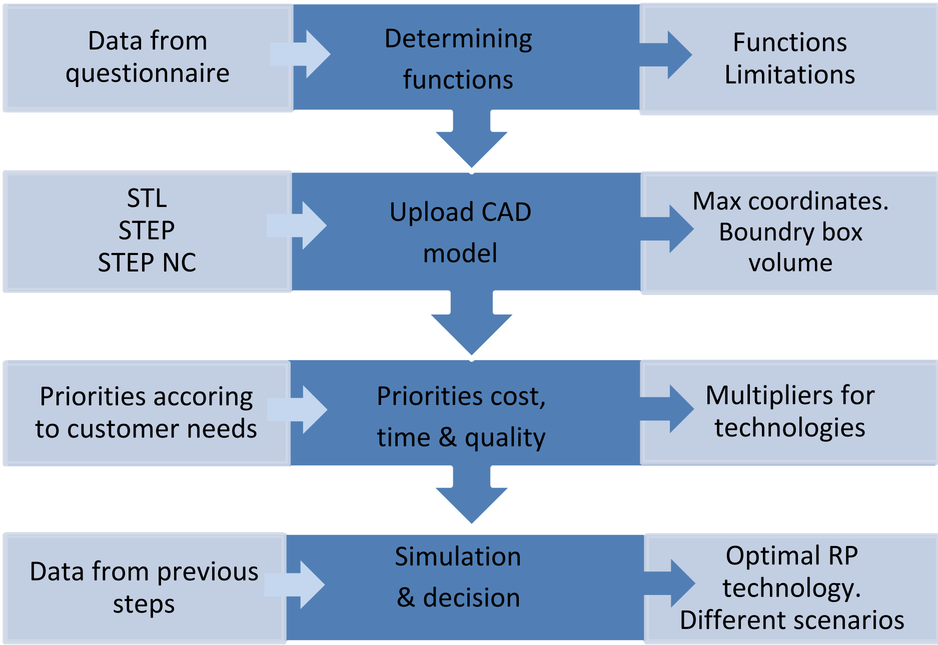


Figure 3.1 Inputs and outputs for each step to determine optimal manufacturing technology in AM. Inputs are shown on the left side and outputs on the right side of the main steps.

3.3 Determining the optimal manufacturing technology for additive manufacturing using software based on functional requirements

The approach described in Chapter 2 can be applied to almost any manufacturing sector. To demonstrate the real life application of this approach additive manufacturing has been chosen as the sector to prove the validity of the concept. The reasons behind choosing AM are twofold: the machines are capable of manufacturing almost any product/geometrical surface which makes the technology selection very sensitive to the function of the product. Almost all of the machines are capable of creating the product but selecting the optimal technology depends on how the product is going to be used (i.e. what are its functions are). The second reason is the availability of these machines, the possibility of testing the theory/method on them and the existing information about products that are manufactured with AM technologies. Products previously manufactured in TUT can be analyzed and checked if the optimal AM machine was used. The AM machines available at TUT are: Formiga 100 by EOS, ZPrinter 310 by ZCorp and 3D Touch Single by 3D Systems. Additional motivation for using AM was also the fact that the field is relatively new and technology selection hasn't been studied in depth in this context.

3.3.1 Structure of the software

A software program was developed to aid in the technology selection process in AM. The program is comprised of three elements: the questionnaire, setting priorities for the product and uploading the CAD model. The questionnaire was created to help specify how and where the product is going to be used (its function). When deciding on whether to use a questionnaire or some other means of defining the functions the main reason for using questions was that the answers can be in form of yes/no or a selection from a list making the answers unambiguous. Questions with free-form answers could probably be used in the future, when functional requirements can be determined from a free-form description of the product (Casamayor *et al.* 2010).

The questionnaire was created by taking products that have been manufactured within the last few years with the AM machines at TUT, then describing their functions and, finally finding the questions that can define them. After that the questions were formed in the best way to find out those functions. As it turned out, two kinds of products were manufactured the most with AM machines: gears and casings. The questionnaire is inclined to identify those two product types but other types of products are recognizable also.

The questionnaire has two types of questions: simple yes/no questions and selection from a list with one possible answer. All answers to both types. have weights assigned to them i.e. they give points to a machine or they eliminate a machine from the consideration. This means that if a yes/no type question as "Yes" (Answer 1), then all the machines receive a certain amount of points. In case of the answer being "No" (Answer 2) there are no points given because all the machines are equal in that aspect. Although the "No" answer do not usually give any points they have to be available as an option, because this makes potential customer think about the relevant feature and whether it is present or affect the product they want to produce and rather than just skip over the question. The same principle is applied to other questions and question types as well. The points are scaled from 1 to 10, where 1 means that the machine has very poor capabilities for producing the function/feature and 10 means that the machine is meant for just that type of a product. All the values for answers (k_{m1}) are integers and constants determined by the compiler of the questionnaire. The points are then summed up to determine the most suitable machine (see Equation 3.1).

Answer values:

Question 1	Question 2	…….	Question n
$M_1 = k_{11}$	$M_1 = k_{12}$	……	$M_1 = k_{1n}$
$M_2 = k_{21}$	$M_2 = k_{22}$	……	$M_2 = k_{2n}$
…………..	…………..	……	…………..
$M_m = k_{m1}$	$M_m = k_{m2}$	……	$M_m = k_{mn}$

Points for the additive manufacturing machines:

$$PM_1 = \sum_{j=1}^{n} k_{1j}$$

$$PM_2 = \sum_{j=1}^{n} k_{2j}$$

$$\dots\dots\dots\dots\dots\dots$$

$$PM_m = \sum_{j=1}^{n} k_{mj}\,, \tag{3.1}$$

where k_{mj} is the answer values for the additive manufacturing machine
PM_m is the sum of the points for the additive manufacturing machine

The evaluation scale refers not to absolute values but to comparison between the machines. For example the question "Does the product have flexible parts (like side-release buckles)?" Because ZPrinter 310 and 3D Touch are capable of making rigid products then in case of the answer being "Yes" then the ZPrinter 310 get 1 point (value of k_{m1}), 3D Touch gets three points and because the products manufactured with Formiga 100 have excellent elastic deformation range that machine gets ten points. But all point assignments depend on the form of the question and how the answers are defined. Some of the answers in the proposed software also have questions for which both answers affect the points given to the machines, usually these questions are about the price or quality of the product.

The second form of the questions is a checkbox list where the respondent can choose one answer from many options and that determines how many points each of the machines gets. For example there is a question in the questionnaire "What's the smallest dimension for the product?" and the answers range from 0,1 mm to 1,0 mm. When the user clicks on one of the checkboxes each of the machine receives a certain number of points depending on the precision of the machine. For example if the smallest dimension of product is 1 mm then ZPrinter 310 would get more points than Formiga 100 because the ZPrinter 310 is more suitable for manufacturing products with less strict measurement precision requirements. Each set of answers to a checkbox list question has its own set of values which shows a linear increase or decrease in most cases. Sometimes the distribution of point values is logarithmic when after a certain point the machine receives substantially more or fewer points. An example would be the question about the forces that affect the product when it is used.

In addition to the points the machines receive according to the answers, with some of the answers also eliminating some of the machines as options or they remove the need to answer certain other questions. For example if the answer to the question "Does the product have to be a certain colour?" is "No" then the question about the colour does not require an answer and can be skipped. If the colour importance question is answered instead with “Yes”, then the next question specifies which colour is required. If we follow the example further, we see that some of the machines will be eliminated as possible candidates for producing the product on bases of the answer i.e. when the product has to be green machines incapable of producing that colour are excluded as a possible result of optimal manufacturing machine. The same principle is applied also to other questions when the positive or negative answer means something very specific that only certain machines are able to produce. Note: in the software there is an asterisk beside the colour question stating that the product can be repainted but this is not part of the service. If the customer plans to repaint the part, the answer to the question “Is the colour of the product important?” should be changed to “No”. This way the machines are not eliminated needlessly. After all of the questions have been answered the points for each of the machines are added up (see Formula 3.1). Figure 3.2 shows what the coding looks like for multiple choice questions. The same code is used for the first type of questions with the *ListItem Text* changed to “yes” or “no” accordingly.

```
<p>
    <asp:label runat="server">How often is the product going to be used/installed?</asp:label>

    <asp:CheckBoxList id="UsedInstalledFrequency" runat="server">
            <asp:ListItem Text="1" Value="1" onclick = "MutExChkList(this);"/>
            <asp:ListItem Text="Up to 10" Value="UpTo10" onclick = "MutExChkList(this);"/>
            <asp:ListItem Text="Up to 100" Value="UpTo100" onclick = "MutExChkList(this);"/>
            <asp:ListItem Text="Up to 1000" Value="UpTo1000" onclick = "MutExChkList(this);"/>
            <asp:ListItem Text="1000+" Value="1000AndMore" onclick = "MutExChkList(this);"/>
    </asp:CheckBoxList>
</p>
```

Figure 3.2 Example of a question with multiple answers.

Figure 3.3 shows how the scores are adjusted according to the answer by the customer. Each answer has its own set of scores that is added to the machines score (addPrinter1Score in the code). Other questions are processed the same way with the exception that when it is a “yes/no” question then the processing is done with “if – then” logic. In addition, for some of the answers presented the same way as described in Fig. 3.3 the results could include elimination of a machine. For example “How often is the product used/installed?” we can specify that for the case “1000AndMore” machine nr 2 is eliminated because the material the machine uses erodes from the product easily in extensive use.

```
private PrinterSuggestionResult processAnswers()
{
    PrinterSuggestionResult result = new PrinterSuggestionResult();
    switch (UsedInstalledFrequency.SelectedItem.Value)
    {
        case "UpTo10":
            result.addPrinter2Score(1);
            break;
        case "UpTo100":
            result.addPrinter1Score(9);
            result.addPrinter2Score(6);
            result.addPrinter3Score(8);
            break;
        case "UpTo1000":
            result.addPrinter1Score(9);
            result.addPrinter2Score(3);
            result.addPrinter3Score(8);
            break;
        case "1000AndMore":
            result.addPrinter1Score(9);
            result.addPrinter2Score(2);
            result.addPrinter3Score(6);
            break;
    }
    return result;
}
```

Figure 3.3 Example of the processing of answers to the question "How often is the product used/installed?"

After the questionnaire has been filled in by the customer, the priorities for the product must be determined. This is done in a way that the customer has to evaluate three parameters on the scale 1 to 5. The categories, as noted above are cost, time and quality. For example if price is paramount then the cost receives a "5" and the time and quality parameters receive a "1". The numeric value assigned for each parameter with this answer is then multiplied by the appropriate value given to each of the machine in that category. Continuing with the paramount cost example then the ZPrinter 310 would get the best results. The calculations are done as shown in Equations 3.1, 3.2 and 3.3 in this chapter. The remaining categories are evaluated in the same way with different value for each of the machine according to its performance in that category. The result of this multiplication is then multiplied by the score that said machine received from the questionnaire, and this is the bases on which the suggestion for the optimal AM machine is made (see Equation 3.2). In addition to the scores the eliminating factors also taken into account and those machines removed from the list of possible machines.

Priority values from the customer

$$\text{Cost} = R_c,\ \text{Time} = R_t,\ \text{Quality} = R_q$$

Priority values for the machines

	Machine 1	Machine 2	……	Machine m
Cost	M_1R_c.	M_2R_c	……	M_mR_c
Time	M_1R_t	M_2R_t	……	M_mR_t
Quality	M_1R_q	M_2R_q	……	M_mR_q

Where the R_c, R_t, R_q values are set by the customer and the $M_1R_c \ldots M_mR_q$ values are set by the questionnaire compiler.

Final score (*FS*) for AM machines

$$FS_1 = PM_1\ (R_c \times M_1R_c + R_t \times M_1R_t + R_q \times M_1R_q)$$
$$FS_2 = PM_2\ (R_c \times M_2R_c + R_t \times M_2R_t + R_q \times M_2R_q)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$FS_m = PM_m\ (R_c \times M_mR_c + R_t \times M_mR_t + R_q \times M_mR_q) \tag{3.2}$$

Optimal manufacturing technology

$$OMT = max\ (FS_1, FS_2, \ldots , FS_m) \tag{3.3}$$

The optimal manufacturing technology (OMT) refers to the most suitable of the machines and that machine is the optimal solution for manufacturing the product in question.

The third part of the software solution involves uploading the CAD/CAM file, parsing and extracting the necessary information from it. The file types that can be used are STEP, STEP-NC and STL. From them the STL file type is the recommended, because it has become the standard that most of the biggest manufacturers of AM machines use and most CAD programs have the option to save that file type. The STL file is then parsed and the coordinates for all of the points the CAD model consists of are identified. To find all of the points coordinates the code in Fig. 3.4 is used.

```
private List<Coordinate> parseStlFile()
{
    List<Coordinate> coordinates = new List<Coordinate>();

    StreamReader reader = new StreamReader(CoordinatesFileUpload.FileContent);

    do
    {
        string textLine = reader.ReadLine();

        if (textLine.Contains(STL_COORDINATE_LINE_PREFIX))
        {
            textLine = textLine.Substring(textLine.IndexOf(STL_COORDINATE_LINE_PREFIX) + STL_COORDINATE_LINE_PREFIX.Length);

            string[] pointCoordinates = textLine.Trim().Split(' ');

            if (pointCoordinates == null || pointCoordinates.Length != 3)
            {
                throw new ArgumentException("One of the coordinates was corrupted, it didn't contain 3 points.");
            }

            Coordinate coordinate = new Coordinate
            {
                x = decimal.Parse(pointCoordinates[0], NumberStyles.Float, CultureInfo.InvariantCulture),
                y = decimal.Parse(pointCoordinates[1], NumberStyles.Float, CultureInfo.InvariantCulture),
                z = decimal.Parse(pointCoordinates[2], NumberStyles.Float, CultureInfo.InvariantCulture)
            };
            coordinates.Add(coordinate);
        }
    } while (reader.Peek() != -1);
    reader.Close();

    return coordinates;
}
```

Figure 3.4 Code for finding coordinates for points in an STL file.

From those point coordinates the maximum and minimum values are found and subtracted from each other giving the maximum length for each of the axis – x, y and z. This means that the zero point for the CAD model does not affect the process. From the maximum lengths for each axis we get boundary box measurements for the product and can calculate its volume.

$$x_{max} - x_{min} = H_x$$
$$y_{max} - y_{min} = H_y$$
$$z_{max} - z_{min} = H_z$$

$$V_{box} = H_x \times H_y \times H_z \tag{3.4}$$

The boundary box is a rectangular prism that surrounds the product which aids to estimate how the product is placed inside the building area of the AM machine. The method that is used at the moment involves first finding the minimum length of the axis and that axis will be oriented in the same direction as the z axis (see Figs. 1.1—1.3) of the AM machines (see Eq. (3.5)).

$$PO_z = min\ (H_x,\ H_y,\ H_z) \tag{3.5}$$

The calculation in Eq. (5) is performed to minimize the number of layers the product consists of. The reason for this is that the cost calculations and estimation of the amount of time for production are based on the number of layers.

The minimal length of the products boundary box is taken and divided by the layer thickness the machine is capable of producing. Then the number of layers is multiplied by the cost per layer. The cost is composed of overhead, preparing the CAD model, depreciation of the AM machine, file slicing and other preparatory works, cleaning the final product, cost of the material and electricity (which is a considerable cost when the machine uses a laser) and turnover tax. Every product is unique and that's why the average values for those components are used to calculate the final cost.

Layer thickness of the AM machines (determined by the machines' manufacture)

$$M_1 = hl_1$$
$$M_2 = hl_2$$
$$\ldots\ldots\ldots\ldots$$
$$M_m = hl_m$$

Number of layers for the product

$$lr_1 = PO_z / hl_1$$
$$lr_2 = PO_z / hl_2$$
$$\ldots\ldots\ldots\ldots$$
$$lr_{\mathrm{m}} = PO_z / hl_m \tag{3.6}$$

Average cost per layer for the AM machines

$$M_1 = c_1$$
$$M_2 = c_2$$
$$\ldots\ldots\ldots\ldots$$
$$M_m = c_m$$

Final cost of the product

$$FC_1 = lr_1 \times c_1$$
$$FC_2 = lr_2 \times c_2$$
$$\ldots\ldots\ldots\ldots$$
$$FC_m = lr_1 \times c_1 \tag{3.7}$$

The estimated time for manufacturing too is calculated based on the number of layers. The time estimation covers preparatory works, preheating of the machine, manufacturing, cleaning and post-processing if needed. The average values for those components are used. Curing after manufacturing is added as a constant value because it does not depend on the product.

Average manufacturing time per layer

$$M_1 = t_1$$
$$M_2 = t_2$$
$$\ldots\ldots\ldots$$
$$M_m = t_m$$

Preheating and curing time for AM machines

$$M_1 = a_1$$
$$M_2 = a_2$$
$$\ldots\ldots\ldots$$
$$M_m = a_m$$

Manufacturing time for AM machines

$$FT_1 = lr_1 \times t_1 + a_1$$
$$FT_2 = lr_2 \times t_2 + a_2$$
$$\ldots\ldots\ldots$$
$$FT_m = lr_m \times t_m + a_m \quad (3.8)$$

It is important to note that the STL files are saved in ASCII format not in binary. The language and the composition in binary code is different from ASCII format and the program is coded for finding coordinates for the latter and also for STEP and STEP-NC.

The software also allows upload of STEP and STEP-NC files. These file formats have been added to make the whole process more user friendly. The second reason for adding these file types is that when using these formats additional information is given, especially with STEP-NC format. This allows the automatic extraction in the future of information about which business area the company belongs to and other information that helps to specify the functions of the product more fully. Finding the point coordinates and defining the boundary box is performed in the same way for STEP format that was used as with STL format. The code is different since the coordinates are presented in a different format but the principle is the same: finding the minimal length of the axis and based on that calculating the production time and cost of the product.

3.4 Determination of the optimal manufacturing technology in additive manufacturing

The results of the software calculations are presented after all the questions have been answered, priorities have been set and the file has been uploaded. All three parts are required or the program, called RapidLab Calculator, gives an error message indicating what missing. The extensions for the file types have also been set to .stl and .stp so other file types cannot be uploaded. The recommendation for the most suitable machine is based on a multiplication operation where the points received from the questionnaire are multiplied by the value set to the different priorities and then again multiplied by the value of each machine for those priorities (Equation 3.3). Example of the questionnaire extract is shown in Fig. 3.5 which actually consists of 17 questions.

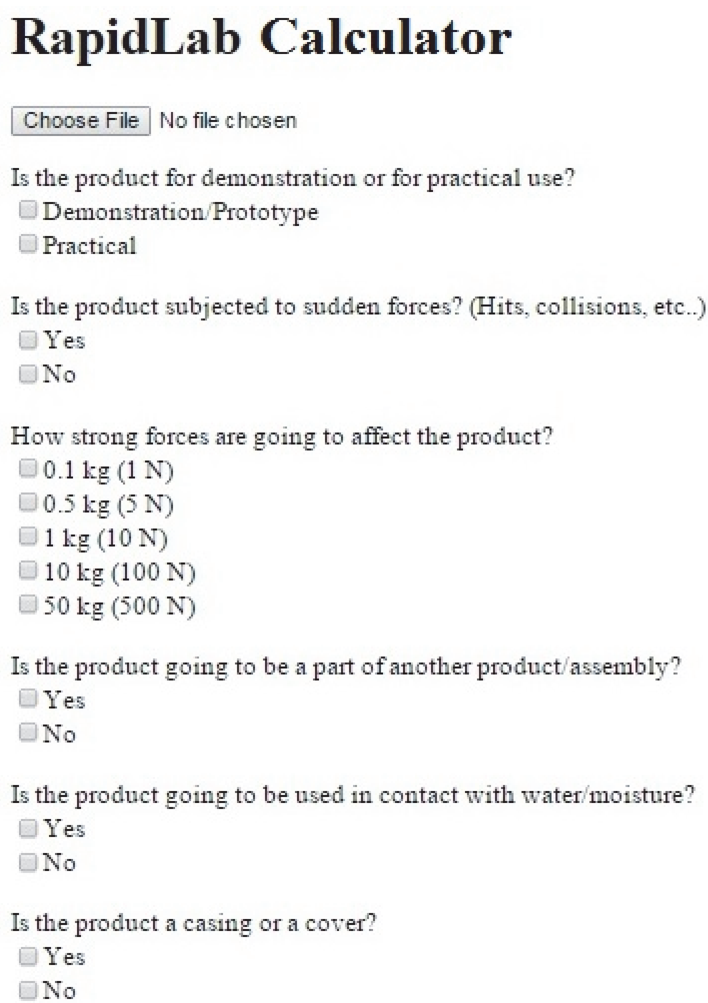


Figure 3.5 Example from the RapidLab Calculator questionnaire.

On the bases of the results a line-up is compiled of the suitable machines, in which the optimal machine would be the one with the highest score. Before the results are displayed the machines are checked for whether they have been ruled out by any of the answers. If they have then they won't be presented as the optimal option and the next machine in line will be suggested. The results for all of the machines are presented to the client. This is done because it gives a better and more comprehensive overview of the various machines and options. The client then can rethink some of the answers and priorities he/she has stated and adjust them accordingly and recalculate the results. An example of this is given in Fig. 3.6.

Figure 3.6 Example results from the RapidLab Calculator program.

The first result that is presented by the program is the most suitable machine, with the relevant information: colour of the material, measurements and volume of the product, how long it takes to manufacture and the price. The price is calculated from the number of layers the product entails.

Presented in addition to the name of the recommended machine, price, estimated time, the colour of the product and dimensions that are presented in the answer there are also the reason for the machines that are not suitable for manufacturing that product (see Fig. 3.6). They are listed below the other information in the results, in a different colour. This allows the client to re-evaluate the answers to the questions and reflect on the true necessity of some the requirements he/she wanted to impose.

At the moment the results presented by the program are not an official price quote and this has been emphasised on the webpage. Before full automation the process of price estimation and optimal technology selection the software has to be tested more thoroughly. The employee who manufactures the final product still has to check whether the recommended machine is the optimal one but the program through semi-automation speeds up that process, makes it easier and reduces the engineer's workload which was the goal.

The Microsoft (MS) .NET Framework was used as the software framework and the programming was done in C#. This is a web based application. Running IIS as an application server is required to run the program.

3.5 Summary of the chapter

As the previous section indicates an expert system RapidLab Calculator that recommends the optimal additive manufacturing machine for manufacturing a product can be constructed based on functional requirements. The system we have developed (software program) is at the moment being tested with already produced products that have been manufactured with the three machines within the last few years at TUT. This is done to verify that the expert system gives the same recommendations about the machines and has similar results for cost and time factor. Products whose data have been input to the program so far have had about 70 % of the same recommendations/results as were used to manufacture them. 30 % of the recommendations have been different mostly because the customer has had a very specific machine in mind for manufacturing the product without considering the alternatives or even being aware of them. About half of that 30 % of result are still questionable or wrong. This means that the questionnaire, answers and weights of the questions need some tweaking to obtain the best results.

The whole process is at the moment in alpha testing phase where it is used by engineers. This means that the results may be different if the software is used by customers the recommendations and results could be different and with less success rate because the customers lack the knowledge that is unintentionally applied when the engineers answers the questions. This will help to find the shortcomings and mistakes in the program. This is the natural way of software development. The next step would be the beta test wherein the participants are regular customers who have ordered multiple products from TUT.

The goals of the expert system are to reduce the workload for the engineers, speed up the technology selection process and reduce the know-how needed by the everyday customers when selecting the optimal AMT. All of these goals have been met with this software program. The customer filling in the questionnaire, uploading the file and setting the priorities by the customer takes remarkably less time than a long explanation from the customer and often answering the exact same questions that are presented in the questionnaire to verify which of the technologies is the most optimal. Accordingly, the program speeds up the process, it reduces workload and thanks to the questionnaire the non-experts get a better overview and recommendations about using the machines. This means more user friendly solution for everyday customer who lacks the know-how in this field. Otherwise, if the only option is to select between ME Proto 7 or PolyJet HD (RedEyeOnDemand 2015) the user has to do a lot of research about the machines before confirming the order. In RapidLab Calculator this issue is resolved.

The main drawback of the program at the moment is the ~15 % of incorrect results and recommendations. As is mentioned above some of the questions probably need a little bit of improving or adding a few more questions could be added to verify the function of the product to improve the accuracy of the results. This means increase in the questionnaires length and because the answers are given by regular users, a very long questionnaire might prove disheartening, leading people to skip the questions altogether. In addition to changing the questions the weight of the answers and priorities for the machines can be modified which can lead to more accurate results.

4 IMPROVING MECHANICAL PROPERTIES OF PRODUCTS MANUFACTURED WITH ADDITIVE MANUFACTURING TECHNOLOGIES

4.1 Mechanical properties of additive manufacturing products

In AM, the product's mechanical properties depend on which technology and which machine are used to manufacture it and properties vary greatly even when using the same AMT but different machines (Cazon *et al.* 2014; Tekinalp *et al.* 2014; Tymrak *et al.* 2014). The base material used (usually in powder form) plays a very important role in the mechanical properties but improving only that material has limited potential and often already bound by physical limitations that are already near the optimal level (in terms of purity, particle size, materials tensile strength *etc*.). The same applies to the binding agent used in various AM machines. This chapter looks at the possibilities for improving the final product's mechanical properties by investigating how product's orientation and post-processing affect the mechanical properties. Similar research has also been done by (Pääsuke 2009; Pilipovic *et al.* 2009; Galeta *et al.* 2013).

It is important to note that the following improvement on properties of the final product itself. The difference between the two lies in the production process itself affecting the products mechanical properties. For example the binding agent used in BJ affects the products mechanical properties and in combination with the base material they make up the final product. In other cases the structure of the base material is changed by melting it (in PBF and ME). Therefore the production process has to be taken into account and the testing of mechanical properties must be conducted with a final product manufactured with AMT, not just the base materials themselves.

The mechanical properties that are measured and the basis for comparison of the products are the following:

σ_m – tensile strength (MPa),
E – modulus of elasticity (GPa),
ε_b – elongation at break (%)
R_a – surface roughness (visual evaluation, µm).

Tensile strength and surface roughness were mentioned in Chapter 3 as properties characterising product's quality and improving them would be the first priority. While modulus of elasticity and elastic elongation are also important, but these factors are even more important for the fragile products (products manufactured with BJT).

Different AM technologies use very different materials and sometimes even the same machine uses different base materials. For example the ZPrinter 310 is able to use three different materials – elastomers, plaster based powders and powder for direct casting. For this reason a universal way of testing and comparing mechanical properties across AM technologies is required. Most of the technologies and new machines focus on plastics and therefore the standards for testing plastic's mechanical properties were the bases on which the specimen are based upon. The standard employed for testing conditions for plastics (EVS-EN ISO 527-2/1B 1993), defines the plastic specimen which dimensions are used and how they are to be tested. The 1B standard was the bases on which the tensile specimen was created. From the same standard, the 1A specimen shape was not chosen because it is meant for directly moulded multipurpose specimen. Such a moulded specimen would have a more unified structure which we does not see in products made with AM technologies. The ISO 527-2 standard suits specimens made with PBF and ME as the base material is plastic. But products made with BJ are essentially composites (composed of base material and binding agent) which complicates the situation. For that testing conditions for plastic composites (EVS-EN ISO 527-4 2010) standard for testing tensile strength of isotropic and orthotropic fiber-reinforced plastic composites was looked into as it is with the most similar structure to BJ products and those of other plaster-based powder AM technologies. The main difference between the ISO 527-4 and ISO 527-4 standards is in the shape of the cross-section which can be a square shape in the EVS-EN ISO 527-4, while all the other measurements remain the same.

The AM technologies that use metals as the base material were also taken into consideration. The standard on testing conditions for metals (EVS-EN ISO 6892-1 2010) is designed for testing of a metal's tensile strength. The specimen in this standard compared to the EVS-EN ISO 527-2 and 527-4 are very similar. Based on these three standards a specimen was created for measuring mechanical properties with various AM machines. It can be produced with any AM machine to test for the required properties and more importantly — the results are all mutually comparable.

To assess if the orientation during manufacturing affects the mechanical properties, differently oriented specimens were made. These specimens were divided into two groups: horizontally and vertically oriented and they are tested to see whether the number of layers and the area of contact between layers have any effect on the mechanical properties. In addition one of the goals of this thesis is to test what kind of influence does post-processing have on the mechanical properties. For that the two groups are again divided into two and finally we have four groups (Sonk *et al.* 2008):

Group 1 – horizontally oriented with post-processing
Group 2 – horizontally oriented without post-processing
Group 3 – vertically oriented with post -processing
Group 4 – vertically oriented without post-processing

In case wherein post-processing is not required the initial division into two groups is sufficient.

4.2 Design of comparative experimental testing in additive manufacturing

One of the criteria for describing the quality of product manufactured with AM machine is the tensile strength of the product. To a great extent, this is what determines where and how the product can be used (what its functionality is) and how well it will hold out during usage. The second criteria for quality is surface roughness (Byun *et al.* 2006) which is a more of a visual property (the distinct visual difference between layers) but it is important because many of the prototypes manufactured with AM technologies are meant for visual representation of the product. These two parameters can be improved by improving the base materials used (with greater purity, smaller particle size, new materials) and by further developing the AM machines (thinner layers, higher accuracy during manufacturing). This sub-chapter focuses instead on the possibilities to improve those two parameter by changing the orientation of products during manufacturing and on the effect of post-processing. In other words – improving the mechanical properties of the product without changing the machinery or the materials used. A different orientation during manufacturing does not require extra expenses, yet affects tensile strength and surface roughness.

Because AM machines and technologies are quite different from one another, a method for testing different products manufactured with different machines is required. The tests have to be repeatable, comparable between machines and achievable with different machines. For that we use a specimen described in Section 4.1 which is designed based on standards ISO 527-2, ISO 527-4 and ISO 6892-1. This specimen can be produced with all AM machines and, because the standards on which the specimen is based on are chosen keeping in mind all the various materials used in AM the results are compatible and comparable. The first step in determining the tensile strength and to a lesser extent the surface roughness of a product manufactured with an AM machine would be to produce and test the specimen described.

The following method is proposed to determine the mechanical properties of a product and how orientation during manufacturing affects them:

1. Defining the finite measurements of the specimen.
2. Producing the specimen with different orientations.
3. Performing post-processing of the product.
4. Carrying out tests with a tensile strength measurement machine.
5. Comparing the results and drawing conclusions.

Step 1 – The specimen measurements have been defined by the ISO 527-2, ISO 527-4 and ISO 6892-1 standards, but in all cases some of the measurements are presented as a range within which the values must fall, for example the length of the narrow parallel-sided portion and radius (see Fig. 4.2). These and some other measurements can be changed without there being an effect on the results so these dimensions should be chosen according to the AM machine capabilities and the specifications for the tensile strength testing machine. For example measurement l_1 has to be greater than 150 mm and if the tensile strength testing machine is unable to test short specimens, this measurement can be adjusted accordingly. The same principle applies to dimension r, which has to be greater than 60 mm but may be increased if necessary. In addition the other measurements have to be specified because, while there is some room for adjusting them, that room is quite limited (± 0,2…0,5 mm). To get the best, comparative result it is advised to not to change the specimen dimensions without compelling reasons. The measurements for the specimens used in the experimentation for this thesis are described in Section 4.3.

Step 2 – The next step is to place the specimen in the building area with different orientations during manufacturing. Vertical and horizontal orientation are recommended because the results will vary most in consequence. There have also been tests wherein the specimens are placed at various angles from 15° to 45° (Pääsuke 2009) but without significant impact on the mechanical properties. The number of specimens manufactured and tested should be enough for a reasonable statistical result, which in this case is five for each orientation.

Step 3 – Post-processing of the specimen according to the technology. In most cases this means removing the specimens from the building area and cleaning them with compressed air, removing any supports or other reinforcements and coating the specimen with resin if necessary. Coating with resin is required for attaining the best mechanical properties for some machines, such as binder jetting machines (as with ZPrinter 310). Post-processing affects the maximum tensile strength and surface roughness. Before testing the tensile strength and modulus of elasticity, the specimens' surface roughness can be evaluated. In most cases this involves simply visual inspection of the specimen because the most critical parameter is the visible distinction between layers. In other words, if the transition from layer to layer is less noticeable, product quality is higher. The traditional methods for evaluating R_a are also applicable too (Pääsuke 2009).

Step 4 – A tensile strength measuring machine is required that can measure the maximum tensile strength, modulus of elasticity and/or elastic elongation (preferably all of these). In addition the machine has to be able to test the specimen at a certain speed (50 mm/min) (ISO 527-2 1993) in order to be in accordance with the ISO standards. The maximum tensile strength measured demonstrates the products ability to withstand static loads. Modulus of elasticity and elastic elongation show how the product behaves when stressed with dynamic loads, for example a blow with a hammer. The elastic properties are especially important for brittle products because these tend to break when dropped on the floor.

Before testing the specimen have to be labeled according to the orientation and post-processing. In this case post-processing involves coating the product with resin, removing support structures and any other modification besides cleaning. If post-processing is necessary then there are four different specimen groups: oriented horizontally and post-processed, oriented horizontally without post-processing, oriented vertically and post-processed and finally oriented vertically without post-processing. If there is no post-processing required, use of two groups is sufficient. This kind of distribution of specimen demonstrates the effect of orientation during manufacturing on the mechanical properties and the effect of post-processing on the same parameters.

Step 5 – The results can be compared to existing materials that are used for prototyping (for example wood or foam plastic), but the main focus here is on comparing the results between groups with different orientation and post-processing and making conclusions based on the observations made. If possible then the results should be compared to other specimen produced with the same testing method but with different AM machines.

An important part of this step is making conclusions based on the tests because it helps to predict the outcome of future tests and helps to improve the mechanical properties of future products manufactured with AM technologies. The conclusions are based on comparison between groups with different orientation and different post-processing and the differences in each group's measured tensile strength, modulus of elastic and elastic elongation. Most important however, is — finding out what are the reasons for the differences between groups if there are any. Making conclusions can be based on a visual inspection of the specimen (with the naked eye or under a microscope) or deductive reasoning. Examples of this are presented in Section 4.3.

When this method was first described, plastic- and plaster powder based AM technologies/machines were intended as the main area of usage. But because testing procedures and standards for metals are identical or very similar then testing the mechanical properties on AM machines that use metal can be done by this method and the results are compatible and comparable.

The inputs and outputs for each of the steps are described in Fig. 4.1.

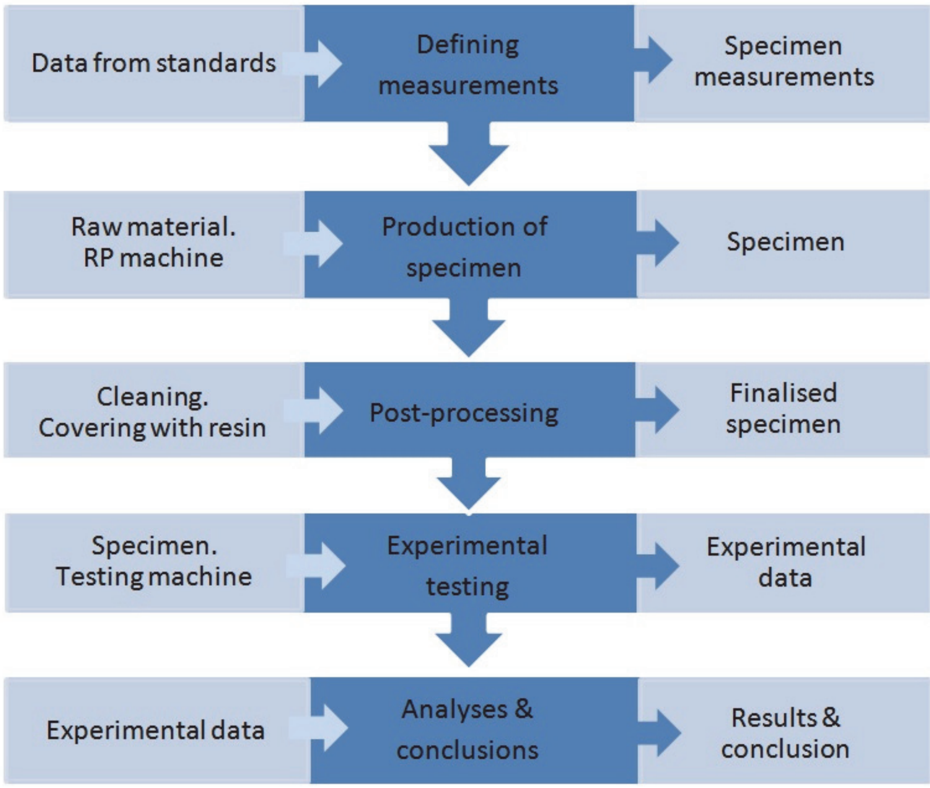


Figure 4.1 Inputs (on the left side) and outputs (on the right) for each step in experimental testing of specimen produces with AM technologies.

4.3 Experimental testing of mechanical properties' dependence on orientation and post-processing

This section describes the choice and production of specimen, their orientation in the building area, execution of experimental testing and conclusions from that testing. Specimens were manufactured with the ZPrinter 310 by ZCorp which uses BJ technology and with Formiga 100 by EOS which uses PBF technology. The specimen in both cases were created with the ISO 527-2, ISO 527-4 and ISO 6892-1 standards as guidance. The reasons for choosing these standards are described at length in Sections 4.1 and 4.2. In short a universal specimen is needed that could be manufactured with all the various AM technologies, would be manufacturable from different materials used today and possibly in the future – different plastics, composites and metals. Tests performed on these specimen must be repeatable in the same conditions and comparable with each other regardless of which AMT was used.

The geometry and measurements of the specimens are shown in Fig. 4.2. These are the recommended measurements for manufacturing of finished products and testing the tensile strength. Some of the dimensions may vary. For example the thickness of specimen (dimension *h*, 4 mm in this case) can be between the value of 2–10 mm according to the ISO 527-2 standard. The specific dimensions for specimen used for tests in this thesis are so that brittle specimen can also be tested (for specimens made with the ZPrinter 310).

4.3.1 Specimens and experimental testing

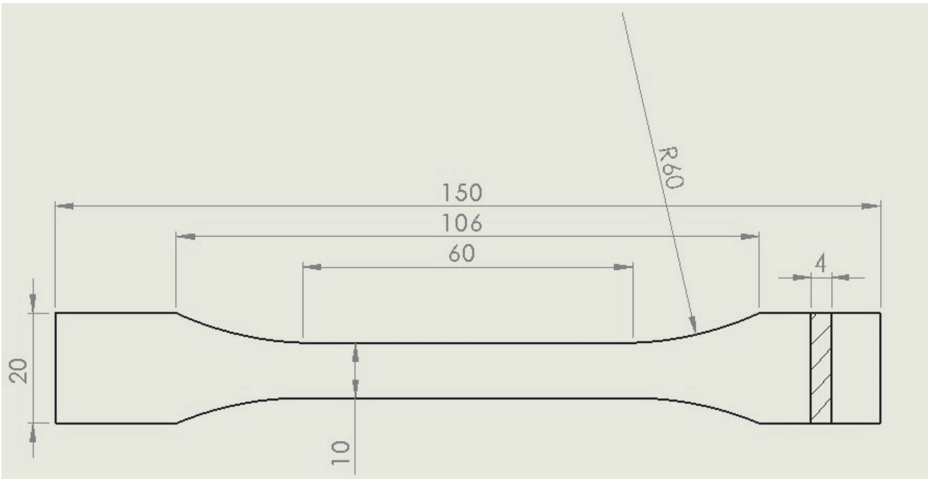


Figure 4.2 Tensile specimens' geometry and measurements.

The specimen for testing were produced to the dimensions shown in Fig. 4.2. To test the effect of difference in orientation during manufacturing the specimen were oriented in two directions: vertically and horizontally. The two groups of specimens were in turn divided into two: one that were post-processed and ones that were not. The goal was to see how large (if any) effect the orientation has on mechanical properties of products and how does the post-processing affect the same properties. From the results conclusions could be drawn to explain the differences in mechanical properties and the reasons behind them. These are described in Section 4.4.

It should be reiterated at this juncture that the mechanical properties of specimens (and other products') manufactured with AM machines are not the same as those of the different powders used to manufacture them. The manufacturing process and the other materials used also affect the final result. For example the plastic powder used in PBF is melted and then resolidified. The new structure is not the same because the cooling temperatures and times are not constant and that affects the mechanical properties of the products. As for the other materials used in post-processing that affect the end-product. Specimen manufactured with the ZPrinter 310 consist of three materials: plaster based powder, biding agent and ZBond resin used for post-processing. The combination of these three result in the final mechanical properties.

Four different mechanical properties were measured: tensile strength, modulus of elasticity, elastic elongation and surface roughness. Tensile strength was one of the properties chosen because it reveals where and how the products can be used and to some extent can be used as a measure of quality. Tensile strength allows to evaluate how large static loads the products can take. Modulus of elasticity shows what dynamic loads (sudden forces, collisions and blows) the product can withstand. Elastic elongation show the deformation products can withstand before breaking. This defines what kind of elastic parts the product can have. For example high elastic elongation percentage means that the product can have click-on fasteners. Surface roughness was evaluated visually because the main parameter for evaluating it is the transition from one layer to another which affects how the product looks. This is one of the quality parameters that separate the machines from each other.

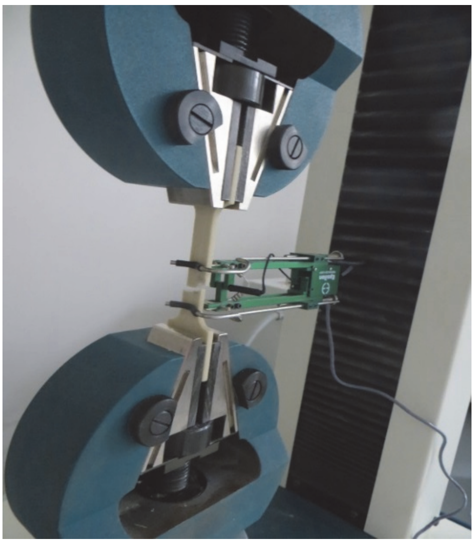


Figure 4.3 Tinius Olsen tensile strength testing machine model H10KT with extensometer.

The experimental testing was done on a Tinius Olsen tensile strength testing machine model H10KT (Fig. 4.3), which has the pulling capacity of 10 kN and testing speed range of 0,001 to 1000 mm/min. This machine is used mainly to test plastics, aluminium and other metals (usually in the form of a flat specimen) and this is why this machine and similar ones are suitable for testing specimen manufactured with AM technologies. Tensile testing machines enables to measure yield force and force at breaking point (for tensile strength). In addition an extensometer model 3542-025M-050-ST manufactured by Epsilon was used that allows measuring the modulus of elasticity and the elastic elongation percentage.

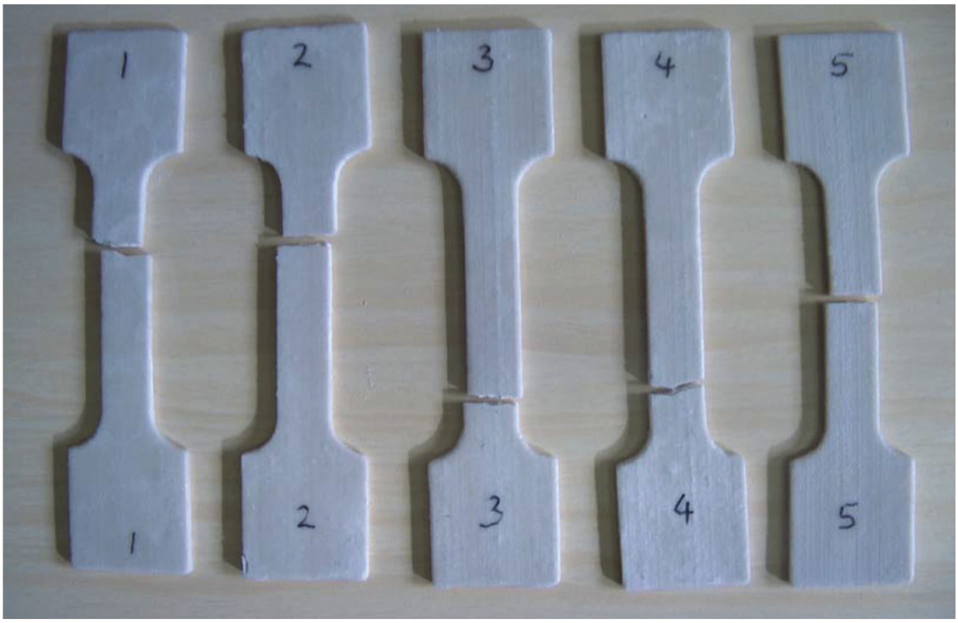


Figure 4.4 Specimen produced with the ZPrinter 310. Group1: horizontally oriented, post-processed.

The specimens shown on Fig. 4.4 are with the same dimensions that are shown on Fig. 4.2 and they are tested on tensile strength machine Tinius Olsen H10KT (Fig. 4.3). As is evident from the figure, the specimens have all broken from different places. This shows that the radius (*r*) between the gripping area and slimmer middle part is enough to avoid stress concentrations because otherwise the specimen would have broken near the radius. The different locations of the fracture along the slimmer middle part show that there are no defects in the manufacturing of the specimens. Otherwise there would be a clear pattern to the fracture locations. All of this means that the geometrical shape and dimensions do not create additional concentration of stress in any one place and that the proposed specimen measurements and geometry can be used in future tests of mechanical properties.

In addition to the specimen group in Fig. 4.4 there are three other groups described in Section 4.1. There were, in total 20 specimens for the ZPrinter 310 and same quantity for the Formiga 100. Specimens were divided equally among the four groups – 5 for each. 5–7 is the recommended amount of specimen to get acceptable results and make conclusions. Five specimens proved to be more than enough for this test because the main goal was to investigate whether there are significant differences in mechanical properties so that rules and recommendations could be worked out for positioning the product in the building area.

4.3.2 Experimental testing of tensile specimen

The test results for the first four specimens are shown in Fig. 4.5. These are the specimens in Table 4.1. There are only four results because the first specimen was tested individually to ensure that the testing conditions were satisfactory and suitable for these specimens. The approach speed and testing speed needed to be tested first because some of the specimens were very fragile and brittle. One of the specimens in another group broke before it could be tested. The right speed was needed to make sure that the specimens had the chance to deform elastically before breaking.

Table 4.1 Test results for the first specimen group: horizontally positioned and post-processed.

Product	2	**Load Range**	500	N
Date	23.04.2007	**Extension Range**	3,000	mm
		Gauge Length	25,00	mm
		Speed	2,000	mm/min
		Approach Speed	1,000	mm/min
		Preload	0	N

Specimen	**Thickness** mm	**Width** mm	**E-Mod** MPa	**Yield** MPa	**Yield Force** N	**Elongation at Yield** %
1	4,000	10,00	4004	5,426	195,3	0,352
2	4,000	10,00	3899	5,639	203,0	0,468
3	4,000	10,00	4238	5,463	196,7	0,212
4	4,000	10,00	3972	5,741	206,7	0,400

Mean	4028	5,57	200,4	0,358
Median	3988	5,55	199,8	0,376
Maximum	4238	5,74	206,7	0,468
Minimum	3899	5,43	195,3	0,212

Specimen	Tensile Strength MPa	Max Force N	Elong at Max %	Elongation %	Stress at Break MPa	Force at Break N
1	5,426	195,3	0,3520	0,4080	5,350	192,6
2	5,639	203,0	0,4680	0,5360	5,526	198,9
3	5,463	196,7	0,2120	0,2120	5,463	196,7
4	5,741	206,7	0,4000	0,4280	5,683	204,6
Mean	5,57	200,4	0,358	0,396	5,51	198,2
Median	5,55	199,8	0,376	0,418	5,49	197,8
Maximum	5,74	206,7	0,468	0,536	5,68	204,6
Minimum	5,43	195,3	0,212	0,212	5,35	192,6

In addition to the numeric data the tensile strength testing machine also presents the results in graphs (as shown in Fig. 4.5) to better elaborate the nature of testing the specimen. Position numbers match those in Table 4.1.

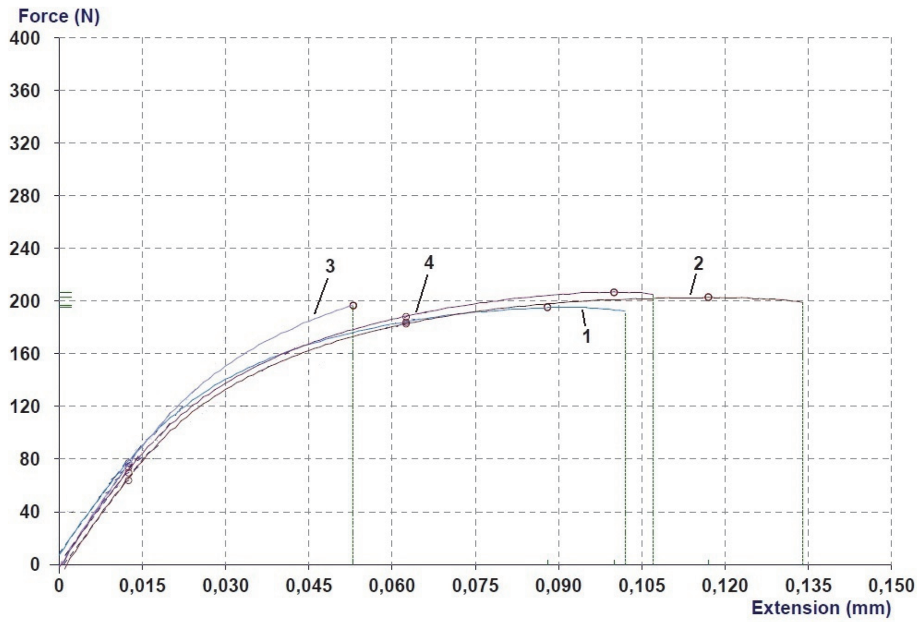


Figure 4.5 Tensile strength graph for group 1: horizontally positioned and post-processed specimens made with the ZPrinter 310.

The first glance at the graph may be a little deceiving because the x axis (Extension) is stretched out. The extension is only 0,135 mm as compared to the testing part dimension of 106 mm. The graph shows that the specimen in group 1 had a very low elastic elongation percentage and the yield strength and tensile strength were identical for all the specimens. This shows that the final products made with the ZPrinter that are horizontally positioned and post-processed are brittle and possess poor mechanical properties. The rest of the results are presented in Subsection 4.3.3 in Table 4.3.

4.3.3 RFID reader housing in comparative additive manufacturing

To get a comparative table for diverse AM technologies and to enable conclusions and recommendations for selecting and using them, two products were manufactured with three different AM machines. The first product – smart dust housing was manufactured with the ZPrinter 310 using BJ technology and a Dimension SST 768 using ME technology. An RFID reader housing (Fig. 4.6) was manufactured with the ZPrinter 310 and a Formiga 100. All four products were made after the same two CAD files and various aspects of the final products were compared. For example the cost of the product, quality, measurements, speed of manufacturing *etc*. These parameter are compared in Table 4.4 (in Subsection 4.4), but this section focuses on the disparities of arithmetic mean of the manufacturing results and how axis calibration and bleed compensation affect the final product with BJ technology.

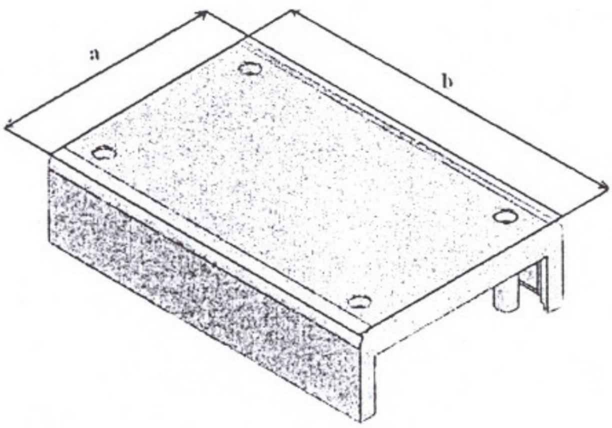


Figure 4.6 Housing for the RFID reader.

The product chosen to be manufactured was housing for a RFID reader (Fig. 4.6). This particular product was chosen because it was manufacturable with all the machines and had real-life use in another Ph.D. thesis (Matsi 2011). The housing was evaluated in different aspects described previously but one of the main goals was the comparison of measurements and accuracy for each of the machines. A TESA micro - hite 3D measuring machine was used to make that comparison. Two dimensions were compared – width (a) and length (b) shown on Figure 4.6.

Table 4.2. Arithmetic mean of measurements disparity on manufacturing result in case of RFID housing in mm.

Dimension ID	CAD model dimension	Disparities of arithmetic mean of manufacturing results	
		BJ	PBF
a	96	0,78	0,37
b	174	0,43	0,18

In addition to comparing the disparities of the arithmetic mean of manufacturing results of the housings also allowed to investigate bleed compensation and axis calibration's effect on the accuracy of dimensions. Both of these factors are relevant to ZPrinter 310 which uses BJ technology because other AM technologies use other parameters. The goal was to investigate how the accuracy of dimensions correlates with changes in these two parameters when cross-sections vary in size and geometric shapes.

Bleed compensation becomes more important when the cross-section of the product has many areas that have one side remarkably longer than the other ones (for example a product that has cooling fins). Increasing the bleed compensation (value drops below 100 %) for these kind of products means that the disparities of arithmetic mean decreases because the amount of binding agent is reduced and it will not "bleed" into areas near the narrow parts of the cross-section. With products that have one large cross-section throughout the product or in which most of the cross-section areas' sides are of similar lengths bleed compensation cannot be used to decrease the disparity in measurements. However in those cases reducing the bleed compensation (value increases above 100 %) can be used to increase the tensile strength of the product because most of that strength comes from the binding agent used.

The extent to which the axis calibration affects the disparity of measurements is dependent on the number of areas in the cross-section. Defects and deviations in dimensions often occur when the printing head moves to start a new area of the cross-section. The printing head moves in two different speeds – working and jogging speeds. Between different parts of the cross-section it moves with jogging speed, which is higher than the working speed. Its stopping position is not always accurate since the printing head's mass causes it to move further because of its inertia. This is why the axis calibration value should be decreased by 2—3 % when the product has many distinct areas in the cross-sections. This allows to reduce the deviations in dimensions compared to the CAD model.

When the cross-section is one big area then the calibration factors should remain at their default values. It is important to note that the axis calibration factors are different for the x and y axis. Both of them should be changed according to the positioning of the product in the building area.

It is recommended that, before applying these principles that a specimen or product to be manufactured and measured and the axis to be calibrated.

4.4 Summary of the chapter

As the experimental tests show the orientation in the building area affects the mechanical properties of products manufactured with AM technologies. When the specimens are produced with a machine using BJ technology the vertical and horizontal positioning affects greatly the maximum tensile strength. For specimens with no post-processing then the tensile strength is remarkably greater (three times as great) on products that are positioned horizontally. The reason behind this is that because the layers have a larger contact surface area between them, the binding agent to increase the bonds between layers and thus increase the tensile strength. Products positioned vertically have significantly less surface area between the layers and this makes the products very fragile and gives them low tensile strength. This is the reason for there being no modulus of elasticity in Table 4.3 – additional equipment needs to be attached to the specimen to measure the modulus (Fig. 4.3) and it caused one of the specimen broke before testing. The surface roughness is also higher in products positioned vertically – the transition from one layer to the next is more clearly evident.

The post-processed products (which in BJ involves covering with a resin (in this case cyanoacrylate ZBond)) have significantly higher tensile strength – up to five times higher compared to specimen with no post-processing. This means that a very high percentage of the product's final tensile strength comes from the resin. The difference in mechanical properties is also remarkably different between vertically and horizontally positioned specimens. When positioned vertically the tensile strength is 25 % higher compared to horizontally positioned specimen. This is the reverse result what was seen when the specimen had no post-processing – the horizontal positioning yielded better results. Even though the same rule applies here that the larger contact surface area between layers increases tensile strength, the resin used for post-processing starts to play a very important role. The resin is usually absorbed to depth of 1mm and thus creating a hardened shell around the product and giving most of the tensile strength the product has. When positioned vertically the resin can penetrate deeper from between the layers and creating a thicker shell and hence a product with better mechanical properties. More layers means more places where the resin can be absorbed deeper into the product and thereby improving the tensile strength. Table 4.3 gives a comprehensive overview of the correlation between positioning and mechanical properties.

When PBF technology is used the similar post-processing as with BJ is not necessary. The products just have to be cleaned of the extra powder and they can be tested. This is why the PBF results in Table 4.3 have only the "no post-processing" section filled. The specimens were positioned in the same way as in BJ and the effects were similar. Because of the larger contact surface area between layers the horizontally oriented specimen were with a higher tensile strength but not as dramatically as in BJ, with the difference of only 5 %. But the positioning does affect the elastic elongation. Horizontally positioned specimen had almost twice the elastic elongation percentage compared to the vertically positioned ones. The reason is that the layers are in the same directions as the force applied later when the products are positioned vertically. The test results show that specimens produced with the Formiga 100 have high manufacturing quality because the tensile strength changes very little when the positioning is changed. Additionally the elastic elongation is dependent on how the product is positioned and how the specimen is later affected by forces. The elastic elongation is increased when the layers of the product have the same orientation as the pulling force.

Table 4.3 Tensile strength test results for the ZPrinter 310 and Formiga 100.

	BJ				**PBF**		
	Force (N)	Tensile stress (MPa)	Elongation at break (%)	Modulus of elasticity (MPa)	Force (N)	Tensile stress (MPa)	Elongation at break (%)
	Vertical positioning, no post-processing						
Ave-rage	21,3	0,591	0,109	-	2025	50,6	9,8
	Horizontal positioning, no post-processing						
Ave-rage	58,2	1,617	0,091	3043	2210	53,2	16,63
	Vertical positioning, post-processed						
Ave-rage	271,1	7,532	0,261	4676			
	Horizontal positioning, post-processed						
Ave-rage	218,4	6,066	0,391	4023			

In addition to the mechanical properties from the specimen testing, the manufacturing of RFID housing formed the base for creating a comprehensive Table 4.4 and is to an extent how the weights to the answers were decided for the RapidLab Calculator software (Chapter 3). The table offers an overview and comparison of various AM technologies based on the machines representing them.

The comparison between machines shows that the disparity of arithmetic means in the measurements is lowest with the Formiga 100 which uses PBF technology followed by the Dimension SST 768 using ME and then the ZPrinter 310 (BJ) having the largest disparity in measurements. The comparison is done for the measurements that are on the same relative axis (x and y) so that peculiarities of products' dimensions and geometric shape did not affect the final results.

Manufacturing speed was also compared but only the manufacturing time of the machine was taken into consideration. The process itself consists of preparatory works, post-processing, cleaning *etc*., which all take time but are dependent on the worker and vary from product to product. Accordingly the comparison was done only based on the machines productivity. Table 4.4 gives the exact times it took the machines to manufacture the housings (Fig. 4.6). In conclusion we can say that the ZPrinter 310 manufacturing time is three times faster than the Dimension SST 768 and 18 times faster than the Formiga 100. Additional time is required for curing and cooling (which is substantial for PBF and BJ) plus cleaning *etc*. but these depend non-linearly on person doing the post-processing and the size of the product.

From the casings produced, the quality of manufacturing was evaluated for each machine. Quality is considered mostly to consist of the surface roughness and the visual appearance of the product. But when comparing the machines the way products can be used and their mechanical properties were also taken into consideration – elastic deformation and tensile strength which determine how and where the products can be used. As expected the quality of manufacturing was highest with the Formiga 100 which was followed by the Dimension SST 768 and finally the ZPrinter 310. However, the quality is compensated with the reverse order of machines' own price, speed of manufacturing and product's price.

The RFID housing axis calibration and bleed compensation's on disparities of arithmetic mean of dimensions was investigated. The impact of these two parameters was looked at on products manufactured with the ZPrinter 310. In previous sections the issue is described in more detail but in short both parameters are affected by the shape and size of the products cross-section. The axis calibration factor should be changed (reduced) when the cross-section consists of many areas. Reducing the calibration factor affects the movement of the printing head and compensates for any possible over-shooting for the area's starting points.

Unlike axis calibration, which is dependent on the number of areas, the bleed compensation is dependent on the shape of the cross-section. If the cross-section has areas with one side considerably longer than the others the bleed compensation should be reduced to limit the flow of binding agent over the designated area. If the product has one big cross-section the bleed compensation should be increased because it does not affect the accuracy that much but increases the strength of the product.

Table 4.4 Comparison of AM technologies

<table>
<tr><th rowspan="2">Estimat-ion criteria</th><th colspan="3">Additive manufacturing technology (including machine's name)</th></tr>
<tr><th>Binder Jetting Technology (ZPrinter 310)</th><th>Material extrusion (Dimension SST 768)</th><th>Powder bed fusion technology (Formiga 100)</th></tr>
<tr><td rowspan="2">Dispari-ties of arithmetic mean of manufactu ring</td><td colspan="2">Compared BJ with ME in one direction (x axis) the BJ disparities of arithmetic mean of manufacturing results is bigger than another direction (y axis)</td><td></td></tr>
<tr><td colspan="3">Compared BJ with PBF the BJ disparities of arithmetic mean of manufacturing results is much bigger then in case of PBF</td></tr>
<tr><td rowspan="2">Speed of manufac-turing</td><td>1 hour 10 minutes (smart dust housing detail) not including:
- covering with resin
-cleaning with compressed air</td><td>3 hours 23 minutes (smart dust housing detail) not including:
-SST Station</td><td></td></tr>
<tr><td>30 minutes (RFID reader housing detail) not including:
-covering with resin
-cleaning with compressed air
-mechanical treatment</td><td></td><td>8 hours and 6 minutes (RFID reader housing detail) not including:
-cooling</td></tr>
<tr><td>Quality of manufac-turing</td><td>Poor</td><td>Good</td><td>Eexcellent</td></tr>
<tr><td>Prepara-tory works</td><td>3D model to STL model; details optimal setting</td><td>3D model to STL model</td><td>3D model to STL model; checking of details</td></tr>
</table>

Post-processing	Need for a mechanical post-processing (resin)	SST Station for automatic wash away of the support structures	Cleaning
Cost of prototype	Low	Low	High
Cost of machine	Low	Average	High
Choice of materials	Fine powder and resin (cyanoacrylate)	Polymer filament	Fine powder

5 CONCLUSIONS

The main objective of this work was to improve selection of the optimal technology by using functional requirements and improvement of the mechanical properties of products manufactured with additive manufacturing technologies.
The three main themes of the thesis can be summarised as: using functional requirements to evaluate the company's manufacturing capability, determining the optimal manufacturing technology in additive manufacturing by using functional requirements and finally improving the mechanical properties and reducing the disparity of measurements in products manufactured with additive manufacturing.

The novelty of this thesis can be listed as follows:

- A novel method is proposed to evaluate a company's manufacturing capability by using functional requirements. This approach speeds up and simplifies the process and reduces workload. In addition the functional requirements approach allows to get the list of the resources needed to manufacture a product. A case study was conducted to verify the approach.

- A novel method is proposed for determining the optimal manufacturing technology in the field of additive manufacturing. The process is quicker, simpler and requires less know-how by the customer than the previous solutions. An expert system was created to verify the method.

- A description has been compiled of the geometry, dimensions and the procedure involved in testing the specimens manufactured with AM technologies to determine the mechanical properties. In addition the correlation between mechanical properties and orientation of products in the building area has been proved. The dependence of disparities in measurements and different variables has been described. Finally, a comprehensive table comparing various AM machines/technologies has been compiled.

The results presented in this thesis show that FRs can be used to model product, process and a company. The model based on FRs allow for a quicker and simpler way to evaluate the manufacturing capability of a company. For this, the company's machinery's functions are compared to the products functions. In addition the model enables to obtain information about the necessary resources to manufacture the product based on the level of details of the model. The main advantage of this approach is in the universal way it can be used because all the different machines and processes can be described with functions. The second advantage is that the process can be semi-automated. The theory, method and specific examples how to use FR in modeling a product, a process or a company are described in connection with this subject.

The second main theme is how FRs can be used to find the optimal manufacturing technology in the field of AM. Theory, method and software have been developed to make finding the optimal manufacturing technology faster, simpler and requiring less know-who by the customer. This approach allows to reduce the workload of engineers handling the price estimates because the software developed also calculates the cost and time required for manufacturing. The reduction in the know-how needed by the customer is done via a questionnaire that defines the function of the product. In contrast, other solutions are limited only to choosing the material and the machine which requires quite extensive research in that field. The developed expert system also gives different scenarios addressing what happens if the product is manufactured with other technology/machine. The specific parts of the code used in the program are presented about how questions are asked in the questionnaire, analyzed and how the geometry of the model is defined.

The third main theme is to improving mechanical properties and reducing disparity of measurements in products manufactured with additive manufacturing. To accomplish both of these goals, no modifications to the machines or development of materials themselves was done but changing the orientation of products, axis calibration and bleed compensation were studied. The thesis proves the orientation has a direct effect on the product's mechanical properties and based on experimental test recommendations were made on how to orient the product. In addition a universal specimen and a method were developed for testing the mechanical properties of products manufactured with AM technologies so that the results can be comparable. Also an overview and comparison of three different AM technology/machine was compiled. Lastly, recommendations for how to change the axis calibration and bleed compensation parameters to decrease disparity of arithmetic mean of measurements have been presented.

The results of this research help to simplify and speed up the evaluation of company's manufacturing capability to produce a given product and allowing finding the optimal manufacturing technology. A description and example of applying these two approaches in the field of AM have been presented. In addition the effect on how orientation of products affects the mechanical properties and different ways to reduce the disparity of measurements is also described.

FURTHER RESEARCH

Functional requirements in company, process and product modelling

One research fields for the future could be development of FR models for a certain field of manufacturing. The structure and creation of the model would remain the same as described in the body of this work, but the models would be more standardized solutions for the peculiarities of that field. This standardization can be implemented by using STEP-NC file format where additional information about the company can be given.

Optimal manufacturing technology selection based on functional requirements

A plan for the future research is to add new machines to the system so that the selection would be wider. This means changes in the part of the program that analyzes the results (Fig. 3.3).

To make the CAD model uploading and usage more user-friendly a module is planned for translating from binary to ASCII in the STL format. At the moment, users are instructed to have the ASCII format because of the way coordinates are presented in that format but creating a translation module and adding other file types as an option to upload is an area to improve the program further.

Experimental testing of specimen manufactured with additive manufacturing technologies

Further research in this field has two distinct directions – new materials and new machines. The same approach and same specimen as proposed in this thesis can be used with different materials and technologies (the main reasons for choosing the shape and size of the specimen).

One of the areas of greatest development is using various metals in additive manufacturing. This opens new areas of application and enables to create more durable products that also can withstand high temperatures. Among these materials are for example stainless steel 17-4 PH, cobalt chrome, Inconel alloy 625, Inconel alloy 718 and there are developments of perfecting the use of titanium as well.

The second are of developing in AM are new machines. Vast majority of them use powder bed fusion for metals. This technology is very similar to PBF and this means that the specimens proposed are also suitable for this technology. Adding new machines to the comparison in experimental testing thus improving Table 4.3 and also adding new machines to the optimal manufacturing selection in AM (Section 4.3). The probability of completion of these future plans are improved as TUT will acquire a metal powder bed fusion machine.

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Author’s contribution: lead author

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Author’s contribution: lead author

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Author’s contribution: tensile strength testing of products manufactured with rapid prototyping, compilation of comparative table, co-author of introduction and literature overview

OTHER PUBLICATIONS

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This thesis is dedicated to my fiancée Kätlin and to T.M – you have been the reason and inspiration for completing this thesis. I can always rely on your love, support, and understanding.

ABSTRACT

Development of additive manufacturing based on functional requirements

The main objectives of thesis were:

1. To test the suitability of using functional requirements to determine manufacturability of a product and to determining optimal manufacturing technology.
2. To simplify and speed up the technology selection process in the field of additive manufacturing.
3. To improve the mechanical properties and decrease the disparity of measurements of products manufactured with additive manufacturing technologies.

A literature overview of functional requirements and examination of existing applications and solutions which use them was completed.

The thesis presents theoretical background on using functional requirements to model a product, a process, and a company. Two different approaches have been described to create those models: the first one deals with how to create a functional model of a manufacturing process or a product through reverse engineering, and in the second one the functional description of the product is done before the manufacturing technology has been determined. In both cases, the result is a comprehensive model that allows evaluating the company's ability to manufacture a product by comparing the product's functional requirements with the company's machinery's functions. The next step (if the manufacturing capability exists) is the comparison of machines to find the optimal manufacturing technology. For this non-functional requirements are used i.e. physical properties that allow comparing price, manufacturing time and productivity.

The result is a method that allows evaluating whether the company in question has the manufacturing capability to produce the product and enables to determine the optimal manufacturing technology in a simple and quick fashion. A case study has been conducted to verify the approach.

Background information and research trends of different AM technologies used in this thesis have been described. Description of three different AMTs is presented. These are the technologies the machines use that are compared in determining the optimal technology and also used in reaching the third goal – increasing the product's quality.

A method for identifying the optimal AM machine has been developed and it has been described as a step-by-step process. Based on this method new software was created that determines the optimal AM machine to manufacture a product. The new expert system, named RapidLab Calculator, recommends an AM machine based on the information provided by the customer and relative

priorities – of cost, time and quality. A questionnaire has been created to determine the functional requirements of the product. Different elements of the coding from the expert system are also shown in the dissertation.

The expert system developed reduces the workload of the engineer, speeds up and simplifies the optimal technology selection process plus reduces the know-how needed by the customer for finding the most suitable machine.

The third objective is to enhance the mechanical properties and reduce disparity of measurements for products manufactured with AM machines. An overview was given of technologies and machines, with the focus on the materials used and on testing the products/materials.

A method has been developed for experimental testing of specimen manufactured with AM machines that assesses the mechanical properties of products and how product orientation affects those properties. The method is presented as a step-by-step process with each step's important aspects and possible pitfalls described. The method describes how the experimental testing procedure is carried out and to which mechanical properties measuring should be focused on.

Great emphasis was placed on the development of specimens' geometry and dimensions. Because AM machines use very different materials it was necessary to take into account the peculiarities of each material, how the specimens can be manufactured and tested so that the results would be comparable. The result is a specimen whose dimensions and geometry allow it to be manufactured with all AM machines and the test results be comparable.

The experimental tests were conducted with differently oriented specimens. The mechanical properties — tensile strength, elastic elongation, modulus of elasticity, and surface roughness were determined along with how products orientation in the building area affects those properties. The test results were analysed and conclusions plus recommendations were made.

The result is a universal specimen that can be manufactured with all AM machines and whose testing results are comparable. The effect of orientation of products in the building area was studied, and conclusions and recommendations are presented. The third main objective of this thesis was completed.

Conclusions

1) A method for using functional requirements to model products, processes and companies was created. These models allow quicker and simpler assessment of companies manufacturing capabilities and determination of the optimal manufacturing technology.

2) A method for determining the optimal manufacturing technology in the field of AM by using functional requirements was created. This method also speeds up, simplifies and reduces the engineer's workload of the whole process.

In addition this method reduces the level of know-how required on the part of the customer.

3) A correlation between the mechanical properties of the product and their dependence on orientation in the building area has been shown. A suitable universal specimen has been created for testing of these properties.

Real-life applications and experimental tests have been conducted to prove the validity of the methods and conclusion presented in this thesis. All the objectives set for this thesis have been met.

KOKKUVÕTE

Funktsionaalsete vajaduste põhine kihtlisandustootmise arendus

Sellel doktoritööl on kolm põhilist eesmärki:

1. Testida funktsionaalsete vajaduste kasutamise sobilikkust toote toodetavuse hindamiseks ning optimaalseima tootmistehnoloogia leidmiseks.
2. Lihtsustada ja kiirendada optimaalse tehnoloogia valiku protsessi kihtlisandustootmise valdkonnas.
3. Kihtlisandustootmise meetoditega valmistatud toodete mehaaniliste omaduste parendamine ning toote mõõtmete hajuvuse vähendamine.

Esimese eesmärgi täitmiseks uuriti doktoritöö raames olemasolevaid lahendusi ning kirjandust, mis käsitleb funktsionaalsete vajaduste kasutamist.

On toodud teoreetiline tagataust funktsionaalsete vajaduste kasutamisest toote, protsessi ja firma mudelite loomiseks. Kirjeldatud on kahte lähenemist: esimene käsitleb olemasoleva tootmisprotsessi või toote funktsionaalse mudeli loomist pöördprojekteerimise teel ning teine, kus toote kirjeldamine funktsioonidena tehakse enne, kui tootmistehnoloogia on määratud. Pakutakse välja meetod nende mudelite loomiseks, mis on toodud selge sammsammulise kirjeldusena. Mõlema lähenemise puhul on tulemuseks mudel, mille põhjal on võimalik hinnata firma võimekust toodet toota, võrreldes toote funktsioone ettevõtte masinapargi võimekusega. Sellest samm edasi (kui võimekus eksisteerib) on sobivate masinate omavaheline võrdlemine leidmaks optimaalseimat varianti. Selleks kasutatakse mittefunktsionaalsete vajaduste omavahelist võrdlemist hinna, aja ja tootlikkuse osas.

Tulemuseks on meetod, mis võimaldab hinnata toote toodetavust ettevõtte poolt ning võimaldab leida optimaalseima tootmistehnoloogia ning kiirendab ja lihtsustab mõlemat protsessi. Selle tõestuseks on tehtud ka juhtumiuuring.

Teise eesmärgi saavutamiseks on esmalt kirjeldatud erinevate kihtlisandustootmisel kasutatavate tehnoloogiate tagataust ning uurimissuunad viimaste aastate jooksul. On toodud kirjeldus kolme erineva kihtlisandustootmise tehnoloogia kohta, mida võrreldakse omavahel optimaalse tehnoloogia valikul. Need tehnoloogiad on ka kasutusel kolmanda põhieesmärgi täitmiseks toodete kvaliteedi tõstmisel.

Optimaalse kihtlisandustootmise masina tuvastamiseks on välja töötatud meetod, mida on kirjeldatud sammsammuliselt. Iga sammu on kirjeldatud ka lähemalt – mis on selle sammu eesmärk, mis peab lõpptulemus olema, et järgnevate staadiumitega edasi minna, ning millised on põhilised vead, mida peaks vältima.

Selle meetodi põhjal on loodud doktoritöö jaoks uudne tarkvaraprogramm hindamaks, milline on optimaalseim kihtlisandustootmise masin toodete valmistamiseks. Loodud ekspertsüsteem RapidLab Calculator võimaldab klientide poolt saadud informatsiooni põhjal pakkuda optimaalseima masina vastavalt kliendi poolt määratud prioriteetidele – hind, aeg või kvaliteet. On loodud küsimustik, mille abil määratakse ära toote funktsioonid ning kasutuse viisid/alad. Doktoritöös on ära toodud ka see, kuidas konkreetsed programmiosad näevad välja koodina.

Tulemuseks on ekspertsüsteem, mis vähendab inseneride töökoormust, kiirendab ja lihtsustab optimaalse tootmistehnoloogia valiku tegemist ning vähendab klientide poolt vajatavat oskusteavet sobiva masina leidmiseks toote valmistamisel.

Kolmandaks eesmärgiks oli parendada kihtlisandustootmise masinatega valmistatavate toodete mehaanilisi omadusi ning vähendada nende mõõtmete hajuvust võrreldes CAD-mudeliga. Selleks on toodud esmalt ülevaade tehnoloogiatest ja masinatest, seal kasutatavatele materjalidest ning nende materjalide testimisest.

Töötati välja meetod eksperimentaalseks katsekehade testimiseks, et määrata erinevate kihtlisandustootmise masinatega valmistatavate toodete mehaanilisi omadusi ning toodete paigutuse mõju nendele omadustele. Nendeks omadusteks on tõmbetugevus, elastsusmoodul, elastne pikenemine ja pinnakaredus.

Suur tähelepanu pöörati katsekehade dimensioneerimisele ja geomeetriale. Kuna kihtlisandustootmise masinad kasutavad väga erinevaid materjale, siis oli vaja arvestada iga materjali iseärasusi ning seda, kuidas neid testida, et tulemused oleksid omavahel võrreldavad ja teste saaks läbi viia kõigil masinatel valmistatud testkehadega. Tulemuseks on katsekeha, mille mõõtmed ja geomeetria võimaldavad seda valmistada kõigil kihtlisandustootmise masinatel ning mille katsetamise tulemused on omavahel võrreldavad.

Viidi läbi eksperimentaalkatsetused erineva paigutusega katsekehadega, mille alusel määrati erinevad mehaanilised omadused ning nende sõltuvus toodete paigutusest ehitusalas. Nende katsete analüüsi põhjal tehti järeldused ning pakuti välja soovitused toodete paigutuseks.

Tulemuseks on järeldused ja soovitused toodete paigutamiseks ehitusalas, põhinedes soovitavatel mehaanilistel omadustel. Lisaks loodi universaalne katsekeha, mida on võimalik valmistada kõigil kihtlisandustootmise masinatel ning mille testimise tulemused on omavahel võrreldavad. Sellega täideti kolmas doktoritöö eesmärk.

Põhijäreldused

1) Loodi meetod funktsionaalsete vajaduste kasutamiseks toote, protsessi ja firma mudeli loomiseks. Selle mudeli abil on võimalik kiiremini, lihtsamalt ning vähema töökoormusega teada saada firma tootmise võimekus ning leida optimaalseim tootmistehnoloogia.

2) Teiseks loodi meetod optimaalse tootmistehnoloogia leidmiseks kihtlisandustootmise masinate hulgast, kasutades funktsionaalseid vajadusi. See meetod samuti kiirendab, lihtsustab ja vähendab inseneri töökoormust selle protsessi juures. Lisaks vähendab see lähenemine tavakasutajate oskusteabe vajadust sobiva masina valimisel.

3) Kolmandaks on näidatud toote mehaaniliste omaduste sõltuvus paigutusest ehitusalas ning on välja töötatud sobiv ja universaalne testkeha nende omaduste määramiseks.

Reaalselt kasutatavad rakendused ja eksperimentaalsed katsetused on läbi viidud, et tõestada töös esitatud meetodite ja järelduste paikapidavust. Kõik töö eesmärgid on sellega täidetud.

APPENDIX A

CURRICULUM VITAE

1. Personal data

Name	Kaimo Sonk
Date and place of birth	22 March 1984, Viljandi, Estonia
Nationality	Estonian
E-mail address	kaimo.sonk@ttu.ee

2. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2007	Product development (MSc, *cum laude*)
Tallinn University of Technology	2005	Product development (BSc)
C.R. Jakobsoni Gymnasium	2002	Advanced English (high-school education)

3. Language competence/skills (fluent, average, basic skills)

Language	Level
Estonian	Fluent
English	Fluent
Russian	Basic skills

4. Special courses

Period	Name of the educational or other organisation
09. 2008	Young scholars workshop, EuroOMA
10.2009	Adobe Flash – multimedia tool for creating animations, TUT
11.2011	Simulation-based development of robot control and applications, Energy and geotechnics doctoral school II
04.2012	Scientific trends in automation and manufacturing, TUT
04.2013	Digital factory for human oriented production system, TUT
11.2014 – 01.2015	Quality learning process in e-environment, TUT

5. Professional employment

Period	Organisation	Position
2004 – 2006	Ensto Ensek	Assistant
2007 – 08.2011	Tallinn University of Technology, Department of Machinery	Assistant
09.2011 – …	Tallinn University of Technology, Department of Machinery	Lecturer

6. Research activity, including honours and theses supervised

Bachelor’s thesis: Camera platform for mobile robot, 2005, Tallinn University of Technology

Master’s thesis: 3 dimensional printing, 2007, Tallinn University of Technology

Supervisor for master’s thesis’s:

Tormis Saar, master’s degree, 2009, (sup) Kaimo Sonk, Design of grip-force measuring gun grip, Tallinn University of Technology, Department of Machinery.

Rene Hanni, master’s degree, 2013, (sup) Kaimo Sonk, Cabin door with high sound isolation, Tallinn University of Technology, Department of Machinery.

Kaarel Pomerants, master’s degree, 2015, (sup) Kaimo Sonk, Forest trailer BMF 152, Tallinn University of Technology, Department of Machinery.

Eesti Raudteed scholarship 2006.
Festo Young Scientist award 2011.

Main areas of scientific work:

- Analysis and development of additive manufacturing processes
- An e-manufacturing concept for SMEs
- Rapid product and process realization - theory and methods
- Mechatronic and production systems proactivity and behavioural models
- Simulation of rapid manufacturing processes, materials and products

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi	Kaimo Sonk
Sünniaeg ja -koht	22 märts 1984, Viljandi, Eesti Vabariik
Kodakondsus	Eesti
E-posti aadress	kaimo.sonk@ttu.ee

2. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2007	Tootearenduse eriala (magister, *cum laude*)
Tallinna Tehnikaülikool	2005	Tootearenduse eriala (bakalaureus)
C.R. Jakobsoni nim. Gümnaasium	2002	Inglise keele eriklass (keskharidus)

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	Kõrgtase
Inglise keel	Kõrgtase
Vene keel	Algtase

4. Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja nimetus
09. 2008	Young scholars töötuba, EuroOMA
10.2009	Adobe Flash – multimeediavahend animatsioon loomiseks, TTÜ
11.2011	Simulatsioonil põhinevrobotite kontrollimine ja rakendused, Energia ja geotehnika doktorikool II
04.2012	Teaduse suunad automatiseerimises ja tootmises, TTÜ
04.2013	Digitaalne tehas inimesele suunatud tootmissüsteemides, TTÜ
11.2014 – 01.2015	Kvaliteetne õppetrotsess e-keskkonnas, TTÜ

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2004 – 2006	Ensto Ensek	Assistent
2007 – 08.2011	Tallinna Tehnikaülikool, masinaehituse instituut	Assistent
09.2011 - …	Tallinna Tehnikaülikool, masinaehituse instituut	Lektor

6. Teadustegevus, sh tunnustused ja juhendatud lõputööd

Bakalaureusetöö: Kaameraplatvorm mobiilsele robotile, 2005, Tallinna Tehnikaülikool

Magistritöö: 3 dimensionaalne printimine, 2007, Tallinna Tehnikaülikool

Juhendaja lõputöödele:

Tormis Saar, magistrikraad, 2009, (juh) Kaimo Sonk, Haardejõudu mõõtva püstoli käepideme projekteerimine, Tallinna Tehnikaülikool, Mehaanikateaduskond, Masinaehituse instituut.

Rene Hanni, magistrikraad, 2013, (juh) Kaimo Sonk, Kõrge heliisolatsioonivõimega kajutiuks, Tallinna Tehnikaülikool, Mehaanikateaduskond, Masinaehituse instituut.

Kaarel Pomerants, magistrikraad, 2015, (juh) Kaimo Sonk, Metsaveohaagis BMF 152, Tallinna Tehnikaülikool, Mehaanikateaduskond, Masinaehituse instituut.

Eesti Raudteede stipendium 2006.
Festo Young Scientist auhind 2011.

Teadustöö projektid:

- Digitaalsete otsetootmisprotsesside analüüs ja arendus
- E-tootmise kontseptsioon väike- ja keskmisega suurusega ettevõtetele
- Kiirvalmistamise protsesside, toodete ja materjalide modelleerimine
- Toodete ja tootmisprotsesside kiire teostamine - teooria ja metodoloogia.
- Mehhatroonika- ja tootmissüsteemide proaktiivsus ja käitumismudelid

DISSERTATIONS DEFENDED AT
TALLINN UNIVERSITY OF TECHNOLOGY ON
MECHANICAL ENGINEERING

1. **Jakob Kübarsepp**. Steel-Bonded Hardmetals. 1992.

2. **Jakub Kõo**. Determination of Residual Stresses in Coatings &Coated Parts. 1994.

3. **Mart Tamre**. Tribocharacteristics of Journal Bearings Unlocated Axis. 1995.

4. **Paul Kallas**. Abrasive Erosion of Powder Materials. 1996.

5. **Jüri Pirso**. Titanium and Chromium Carbide Based Cermets. 1996.

6. **Heinrich Reshetnyak**. Hard Metals Serviceability in Sheet Metal Forming Operations. 1996.

7. **Arvi Kruusing**. Magnetic Microdevices and Their Fabrication methods. 1997.

8. **Roberto Carmona Davila**. Some Contributions to the Quality Control in Motor Car Industry. 1999.

9. **Harri Annuka**. Characterization and Application of TiC-Based Iron Alloys Bonded Cermets. 1999.

10. **Irina Hussainova**. Investigation of Particle-Wall Collision and Erosion Prediction. 1999.

11. **Edi Kulderknup**. Reliability and Uncertainty of Quality Measurement. 2000.

12. **Vitali Podgurski**. Laser Ablation and Thermal Evaporation of Thin Films and Structures. 2001.

13. **Igor Penkov**. Strength Investigation of Threaded Joints Under Static and Dynamic Loading. 2001.

14. **Martin Eerme**. Structural Modelling of Engineering Products and Realisation of Computer-Based Environment for Product Development. 2001.

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36. **Lauri Kollo**. Sinter/HIP Technology of TiC-Based Cermets. 2007.

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39. **Eduard Ševtšenko**. Intelligent Decision Support System for the Network of Collaborative SME-s. 2007.

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41. **Kristo Karjust**. Integrated Product Development and Production Technology of Large Composite Plastic Products. 2008.

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89. **Tanel Aruväli**. Wireless Real-time Monitoring of Machining Processes. 2015.

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